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MORPHOLOGICAL AND STRUCTURAL CRYSTALLOGRAPHY AND OPTICAL PROPERTIES OF SILICON CARBIDE (SiC)*

PART I: MORPHOLOGICAL CRYSTALLOGRAPHY AND ETCHING FIGURES

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ABSTRACT

The morphological crystallography of β -SiC (cubic), and of five modifications or "types" of α -SiC (hexagonal), two of them new, is given in detail. Each of the α -SiC types is characterized by its own series of crystal forms, those of types I, IV and VI being typical for crystals based on rhombohedral lattices, while those of types II and III are characteristic of hexagonal lattices. Each α -SiC type must be referred to its own axial ratio, all of which, however, are rationally related, and the crystal forms common to two or more of the types are those whose indices are equivalent when referred to the greatest common divisor axial ratio. Two or more of the hexagonal modifications often coalesce in such a

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manner that c and a axes are common and the basal pinacoids form the plane of contact. Two methods of twinning were noted. In the more common case it was impossible to distinguish between two possible laws: twinning axis perpendicular to a common first order pyramid, or twinning plane parallel to a very rare first order pyramid. The second twinning arrangement, involving only type I crystals, obeys the law: twinning axis, the c axis. Crystal measurements made on β -SiC for the first time indicate the hextetrahedral class of the isometric system. Beta SiC is commonly intergrown with α -SiC in such a manner that tetrahedron faces of the former are in contact with or parallel to basal pinacoids of the latter.

Etching figures obtained on crystals of the α -SiC types by the use of Cl_2 at 1000°C . and by fused borax indicate that α -SiC, types I, IV and VI are ditrigonal-pyramidal, and that types II and III are dihexagonal-pyramidal. Etching phenomena reveal that purely morphological criteria are inadequate for the distinction between upper and lower basal pinacoids.

INTRODUCTION

Many studies have been made of the morphology and structure of silicon carbide, and of its physical properties, including density and indices of refraction, but there has been no attempt to correlate the data for the many observed modifications, nor to seek the relationships among them. Moreover, in addition to the lack of consistency and the incompleteness of the literature on the subject, little work has been done on crystals of known chemical analysis. For these reasons it seemed advisable to undertake a detailed study of the morphological and structural crystallography, and the optical constants of this substance.

The investigation has been carried out in the Laboratories of Norton Company, with the exception of the x -ray determinations which were made in the Mineralogical Laboratory at the University of Michigan. Although silicon carbide manufactured by the Norton Company under the trade name "cristolon" supplied most of the material for the study, commercial SiC manufactured by all the American and most of the important foreign producers was included.

ACKNOWLEDGMENTS

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MORPHOLOGICAL CRYSTALLOGRAPHY

REVIEW OF LITERATURE

Frazier (1893) examined platy crystals of SiC, the yellow-green of which showed a distinct rhombohedral-like development while the blue were apparently hexagonal holohedral. The axial ratio and most of the crystal forms observed by Frazier as well as by subsequent investigators are contained in Table 1, while forms which must be considered uncertain are listed in Table 2. The one twin observed was said to obey the law: twinning plane, the unit rhombohedron (now designated by the letter r).

Becke (1895) studied poorly developed tabular crystals. He also described twins similar to that observed by Frazier, but recognized two possible laws: (1) twinning axis normal to the unit trigonal pyramid (now designated r), or (2) twinning plane the form $(10\bar{1}4)$ (now represented by E). Becke believed the first possibility to be more likely since it is a more common twinning law.

Negri (1902) measured almost a hundred SiC crystals, some of which were apparently hexagonal holohedral, while others appeared to be rhombohedral. He, however, referred them all to the hexagonal-scalenohedral class. A later investigation which was to have included the results of etching experiments, and a discussion of 22 other rare and very rare forms was unfortunately never published.*

Baumhauer (1912), studying 20 small tabular SiC crystals, divided them into three groups, or "types," each having its own characteristic suite of forms, but referred them all to the same axial ratio. Some forms were common to two types, but only the base was common to all three. Crystals of the first type clearly showed a rhombohedral-like development and were considered hexagonal-scalenohedral, while those of types II and III were apparently holohedral and said to be dihexagonal-dipyramidal. Crystals of the different types were adjacent to and irregularly intergrown with one another, and in two cases there was a coalescence of types I and II in such a manner that, although each crystal was apparently single and homogeneous, all the faces adjacent to one base were those of type I while all faces adjacent to the other base belonged to type II. The plane of contact between the two types was parallel to both basal pinacoids. The yellow crystals were found to be type I, the green, type II, while all three types were represented by the dark blue and black SiC.

Baumhauer (1915) described additional cases of coalescences of the SiC

* Personal communication from Professor A. Pelloux, Director, Institute di Mineralogia, Genoa, Italy, August 26, 1939.

types. Evidence for hemimorphism was afforded by the distribution of iridescent coatings on the various crystal faces, so Baumhauer considered type I ditrigonal-pyramidal. Certain triangular markings discussed more fully later led him to conclude that type II also belonged to the same class. Type III was considered dihexagonal-pyramidal. Two modes of twinning were reported: twinning plane the first order prism, and twinning plane the basal pinacoid.

Weigel (1916) observed many crystals of hexagonal SiC whose twinning plane was said to be that of a pyramid.

Espig (1921) confirmed Baumhauer's observations of SiC types and coalescences, and twinning parallel to the base. Crystals of type I were said to be yellow-green, while those of type II were blue.

The crystal of cubic SiC studied by Braekken (1930) was reported to be octahedral with poor skeletal faces, but apparently no goniometric measurements were attempted.

Peacock and Schroeder (1934) studied thin tabular crystals all of which proved to be type II. The indices of the forms of all the known SiC types were simplified to the greatest possible extent by referring each type to its own individual axial ratio, namely, that resulting from the x-ray studies of Ott (1925*a*, 1925*b*, 1926).

Appended to the above article, Peacock (1934) has described SiC crystals in the collection at Harvard University. The forms listed in Table 1 under type I were observed.

Cortelezzi and Schroeder (1934) studied type II crystals, some or all of which were apparently the same as those studied by Peacock and Schroeder.

The Handbook of Chemistry and Physics (1943) and Wyckoff (1931) refer to the three modifications of SiC mentioned above as SiC I, II and III. Cubic SiC is designated SiC IV, and the hexagonal modification with 51 formula weights per cell as described by Ott (1928) is noted as SiC V.

Table 1, which correlates the crystal forms observed by the different authors, is divided by heavy vertical lines into four major sections. The earlier investigators referred all crystals to the same $c:a$ ratio, but did not distinguish definite crystal types. Later Baumhauer and Espig each recognized three definite types but referred all to an axial ratio twice that of the earlier writers. Peacock and Schroeder, Peacock, and Cortelezzi and Schroeder recognized the three types but referred each to its own unique axial ratio. Finally, the present writer has distinguished five crystal types each with its own c value and has for the first time definitely differentiated between upper and lower forms by etching methods.

There is some doubt as to the number of types observed by the early investigators and the proper correlation of forms later found to be com-

TABLE 1. CORRELATION OF ESTABLISHED FORMS ON α -SiC

Frazier (1893)	Becke (1895)	Negri (1902)	Baumhauer (1912), (1915)	Espig (1921)	Peacock and Schroeder (1934), Peacock (1934)	Cortelezzi and Schroeder (1934)	Thibault	Calculated angle to base	α -SiC Type
$c=1.2264$ base — 1 10/7 5/2 10 — 10/11 5/4 2 5 —	$c=1.2243^*$ (0001) OR — (10 $\bar{1}$ 1) R ? (10.0.10.7) 10/7R (50 $\bar{5}$ 2) 5/2R (10.0.10.1) 10R — — (20 $\bar{2}$ 1) 2R ? (50 $\bar{5}$ 1) 5R —	$c=1.2266$ (111) (23.23. $\bar{7}$) (100); (22 $\bar{1}$) ? (17.17.13); (9 $\bar{1}$ $\bar{1}$) (778) (11.11. $\bar{19}$) — (31.1.1); (77 $\bar{3}$) (14.1.1) (5 $\bar{1}$ $\bar{1}$); (11 $\bar{1}$) ? (11.4.4) —	$c=2.4532$ OR (111)(0001) —5/13R (166)(5.0. $\bar{5}$.13) —1/2R (011) (10 $\bar{1}$ 2) —5/7R (144) (5057) —5/4R (233) (5054) —5R (322) (5051) — 5/11R (722) (5.0. $\bar{5}$.11) 5/8R (611) (5.0. $\bar{5}$.8) R (100) (10 $\bar{1}$ 1) 5/2R (4 $\bar{1}$ $\bar{1}$) (5052) —	$c=2.4538$ (0001); (000 $\bar{1}$) — (10 $\bar{1}$ 2)?; (10 $\bar{1}$ 2) (5057); (5057) (5054); (5054) (5051); (5051) — (5.0. $\bar{5}$.11) (5058); (5058) (10 $\bar{1}$ 1); (10 $\bar{1}$ 1) (5052); (5052) —	$c=12.2660$ c , 0(0001) m , —1/13 (1.0. $\bar{1}$.13) r , —1/10 (1.0. $\bar{1}$.10) f , —1/7 (10 $\bar{1}$ 7) g , —1/4 (1014) z , —1 (1011) k , +1/14 (1.0. $\bar{1}$.14) h , +1/11 (1.0. $\bar{1}$.11) i , +1/8 (1018) x , +1/5 (1015) e , +1/2 (10 $\bar{1}$ 2) —	— — — — — — — — — — — —	$c=12.267_6$ c (0001); \bar{c} (000 $\bar{1}$) M (1.0. $\bar{1}$.13) r (1.0. $\bar{1}$.10) f (1017); \bar{f} (01 $\bar{1}$ 7) g (1014); \bar{g} (0114) z (1011); \bar{z} (0111) k (1.0. $\bar{1}$.14) h (0.1. $\bar{1}$.11); \bar{h} (1.0. $\bar{1}$.11) i (0118); \bar{i} (1018) x (0115); \bar{x} (1015) e (0112); \bar{e} (10 $\bar{1}$ 2) b (1.1.2.15)	0°00' 47°27 $\frac{1}{2}$ ' 54°47' 63°42' 74°14' 85°57 $\frac{1}{2}$ ' 45°20' 52°10' 60°32 $\frac{1}{2}$ ' 70°33 $\frac{1}{2}$ ' 81°58' 58°33 $\frac{1}{2}$ '	I
base first order prism 4/5 1 ? 4/3 2 ? 4 —	(0001) OR (10 $\bar{1}$ 0) ∞ R — (10 $\bar{1}$ 1) R ? (4043) 4/3R (20 $\bar{2}$ 1) 2R ? (4041) 4R —	(111) (2 $\bar{1}$ $\bar{1}$) ? (13.1.1); (33 $\bar{1}$) (100); (22 $\bar{1}$) ? (11.1.1); (77 $\bar{5}$) ? (5 $\bar{1}$ $\bar{1}$); (11 $\bar{1}$) ? (311); (557) —	$c=2.4532$ \pm OP (111) (0001); ($\bar{1}$ $\bar{1}$ $\bar{1}$) (000 $\bar{1}$) ∞ P (2 $\bar{1}$ $\bar{1}$) (10 $\bar{1}$ 0) \pm 2/5P (311) (2025); ($\bar{1}$ $\bar{7}$ $\bar{7}$) (2025) \pm 1/2P (411) (1012); (011) (1012) \pm 2/3P (711) (2023); (155) (2023) \pm P (100) (1011); (122) (10 $\bar{1}$ 1) \pm 2P (5 $\bar{1}$ $\bar{1}$) (20 $\bar{2}$ 1); (111) (2021) —	$c=2.4538$ (0001); (000 $\bar{1}$) (10 $\bar{1}$ 0) — (10 $\bar{1}$ 2); (10 $\bar{1}$ 2) (2023); (2023) (1011); (1011) (2021); (2021) —	$c=4.9064$ c , 0 (0001) a , ∞ (10 $\bar{1}$ 0) — r , 1/4 (10 $\bar{1}$ 4) s , 1/3 (1013) x , 1/2 (10 $\bar{1}$ 2) y , 1 (1011) —	$c=4.9065$ c , 0 (0001) a , ∞ (10 $\bar{1}$ 0) — r , 1/4 (10 $\bar{1}$ 4) s , 1/3 (1013) x , 1/2 (10 $\bar{1}$ 2) y , 1 (1011) —	$c=4.9070$ c (0001); \bar{c} (000 $\bar{1}$) m (10 $\bar{1}$ 0) n^* (1015); \bar{n} (1015) r (1014); \bar{r} (1014) s (1013); \bar{s} (1013) x (1012); \bar{x} (1012) y (1011); \bar{y} (1011) b (1126)	0°00' 90°00' 48°34 $\frac{1}{2}$ ' 54°47' 62°06' 70°33 $\frac{1}{2}$ ' 79°59 $\frac{1}{2}$ ' 58°33 $\frac{1}{2}$ '	II
?	?	(111) (2 $\bar{1}$ $\bar{1}$) ? (25.1.1); (17.17. $\bar{7}$) — (11. $\bar{1}$.1); (77 $\bar{5}$) ? (19.5.5); (11.11.13) —	$c=2.4532$ \pm OP (111) (0001); ($\bar{1}$ $\bar{1}$ $\bar{1}$) (000 $\bar{1}$) ∞ P (2 $\bar{1}$ $\bar{1}$) (10 $\bar{1}$ 0) \pm 4/9P (17.5.5) (4049)?; (1.13.13) (4049) \pm 2/3P (711) (2023); (155) (2023) \pm 4/3P (11. $\bar{1}$.1) (4043); (577) (4043) —	$c=2.4538$ (0001); (000 $\bar{1}$) (10 $\bar{1}$ 0) — (4049) (2023); (2023) (4043); (4043) —	$c=3.2709^*$ — — — — — — —	— — — — — — — —	$c=3.2713$ c (0001); \bar{c} (000 $\bar{1}$) m (10 $\bar{1}$ 0) — d^* (10 $\bar{1}$ 3) s (1012); \bar{s} (10 $\bar{1}$ 2) l^* (10 $\bar{1}$ 1); \bar{l} (1011) b (1124)	0°00' 90°00' — 51°32 $\frac{1}{2}$ ' 62°06' 75°10 $\frac{1}{2}$ ' 58°33 $\frac{1}{2}$ '	III
				$c=2.4538^*$ (7075); (7075) (7072); (7072) — (7.0. $\bar{7}$.10); (7.0. $\bar{7}$.10) (7074); (7074) (7071) —	— — — — — — — —	— — — — — — — —	$c=17.174_6$ c (0001); \bar{c} (000 $\bar{1}$) N (0.1. $\bar{1}$.11); \bar{N} (1.0. $\bar{1}$.11) G (0118); \bar{G} (1018) L (0115) K (0112); \bar{K} (10 $\bar{1}$ 2) O (0.1. $\bar{1}$.19) \bar{O} (0.1. $\bar{1}$.16) P (0.1. $\bar{1}$.13) H (1.0. $\bar{1}$.10); \bar{H} (0.1. $\bar{1}$.10) I (10 $\bar{1}$ 4); \bar{I} (0117) J (1011); \bar{J} (0111)	0°00' 60°59' 68°02' 75°51' 84°14 $\frac{1}{2}$ ' 46°13 $\frac{1}{2}$ ' 51°06' 56°45' 63°14 $\frac{1}{2}$ ' 70°33 $\frac{1}{2}$ ' 78°36' 87°07'	IV
				$c=2.4538^*$ (11.0.11.5) ?	—	—	No morphological data available. Type established by Ott (1920) from x-ray study.		V
							$c=26.989$ c (0001) C (1.0. $\bar{1}$.28) r (1.0. $\bar{1}$.22) u (1.0. $\bar{1}$.16); \bar{u} (0.1. $\bar{1}$.16) l (1.0. $\bar{1}$.13); \bar{l} (0.1. $\bar{1}$.13) q (1.0. $\bar{1}$.10); \bar{q} (0.1. $\bar{1}$.10) p (1017); \bar{p} (0117) o (1014); \bar{o} (0114) j (1011); \bar{j} (0111) D (0.1. $\bar{1}$.26) B (0.1. $\bar{1}$.23); \bar{B} (1.0. $\bar{1}$.23) A (1.0. $\bar{1}$.20) w (0.1. $\bar{1}$.17); \bar{w} (1.0. $\bar{1}$.17) x (0.1. $\bar{1}$.11); \bar{x} (1.0. $\bar{1}$.11) v (0115); \bar{v} (1015)	0°00' 48°03 $\frac{1}{2}$ ' 54°47' 62°49 $\frac{1}{2}$ ' 67°21 $\frac{1}{2}$ ' 72°12 $\frac{1}{2}$ ' 77°20 $\frac{1}{2}$ ' 82°41' 88°09 $\frac{1}{2}$ ' 50°09 $\frac{1}{2}$ ' 53°34 $\frac{1}{2}$ ' 57°18 $\frac{1}{2}$ ' 61°23' 70°33 $\frac{1}{2}$ ' 80°53'	VI

*Calculated from twinning angles.

* Types IV and VI not recognized as distinct types by Espig.

* Calculated from previous data. No type III crystals observed by these authors.

* Letters assigned by Peacock and Schroeder although they did not observe these forms.



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TABLE 2. UNCERTAIN FORMS ON α -SiC

Angle to Base		Letter	Symbol	(when) $c=$	Observed by	α -SiC type	Times Observed
Observed	Calculated						
?	15°49'*	—	1/5	1.2264	Frazier (1893)	?	?
?	81°32 $\frac{1}{2}$ '*	—	19/4	1.2264	Frazier (1893)	?	?
35°20'	35°18 $\frac{1}{2}$ '	E**	(10 $\bar{1}$ 4)	2.4532	{Baumhauer (1915) Espig (1921)	I	1
43°20 $\frac{1}{2}$ '	43°21 $\frac{1}{2}$ '	—	(10 $\bar{1}$ 3)	2.4532	Baumhauer (1915)	?	1
?	57°34 $\frac{1}{2}$ '*	—	{(50 $\bar{5}$ 9)} (50 $\bar{5}$ 9)}	2.4538	Espig (1921)	III	1
?	87°58 $\frac{1}{2}$ '*	—	(10.0.10.1)	2.4538	Espig (1921)	?	2
84°55'	84°57 $\frac{1}{2}$ '	—	(2021)	4.9070	Thibault	IP	1
70°29'	70°33 $\frac{1}{2}$ '	x	(10 $\bar{1}$ 7)	17.174 ₅	Thibault	II	1
50°16 $\frac{1}{2}$ '	50°09 $\frac{1}{2}$ '	\bar{D}	(0.1.1.26)	26.989	Thibault	IV	1
48°24'	48°03 $\frac{1}{2}$ '	\bar{C}	(1.0.1.28)	26.989	Thibault	VI	1
54°49'	54°47'	\bar{r}	(1.0.1.22)	26.989	Thibault	VI	1

* Calculated from symbols and axial ratios given by the authors.

** Letter assigned by the writer to facilitate reference to the form in connection with twinning.

mon to two types. This is indicated by question marks in Table 1. Except in one case Espig gave no observed angles for the forms which he listed, and, from the data which he presented, the writer was not able to gain a clear conception of the combination of forms or types on many of the crystals which he described. For example, although the indices given for several forms would indicate that Espig observed faces belonging to the new modification now designated α -SiC, type IV, these faces did not always occur in the proper sequence and faces of forms belonging to other hexagonal SiC modifications were interspersed in an irregular manner. The same may be said of $(11.0.\overline{11}.5)$ which is equivalent to one of the forms of the new modification, type VI. Espig apparently recognized only modifications I, II and III, and did not explain the presence of these faces which did not belong to the simple arithmetical series of forms of the first three types. Although these forms might be considered questionable, they are included in Table 1 for the purpose of correlation with equivalent forms now definitely established.

ALPHA SiC

Introduction. Commercial abrasive silicon carbide consists very largely of hexagonal or α -SiC crystals in all states of perfection, intergrowths and aggregates of subhedral crystals and dense crystalline masses. Usually small amounts of cubic or β -SiC and certain impurities are also present.

Euhedral crystals are most frequently tabular parallel to the base. In such a case one basal pinacoid is usually well developed while the other is poorly developed or absent altogether, but this is not universal. Less commonly the individuals are thick tabular to equant, and rarely, elongated parallel to the c axis. Crystals showing skeletal growth with prisms and pyramids accompanied by many horizontal striae and re-entrant angles are very common.

About a hundred and fifty crystals were completely measured during the course of this study, and, in addition, certain zones on about five hundred more were investigated. A one-circle goniometer was used almost exclusively.

Type I. This type is apparently the second most common of the α -SiC modifications. As indicated by Tables 3 and 4, and Fig. 1, the crystals are rhombohedral-like in development as evidenced by the different series of forms characteristic of alternate first order trigonal pyramid zones. One very small black crystal contained five faces of the new form \bar{b} . In this case, as well as with individuals of types II and III and 24 minute crystals of undetermined type examined under the stereoscopic microscope, all faces of the second order pyramid occurred adjacent to only one of the basal pinacoids which etching showed to be the lower form.

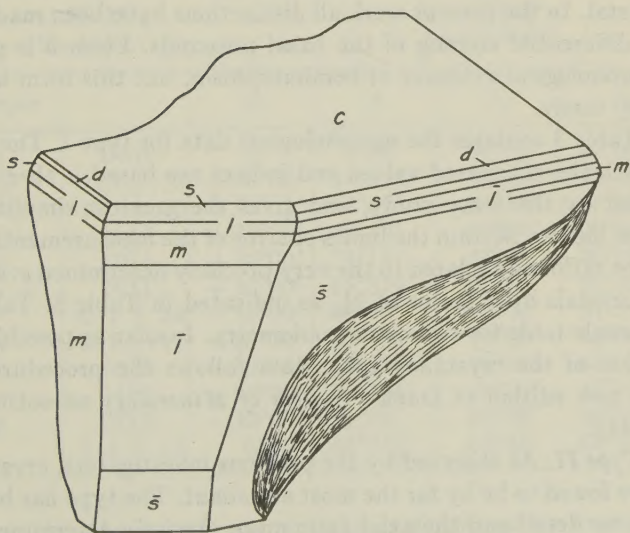
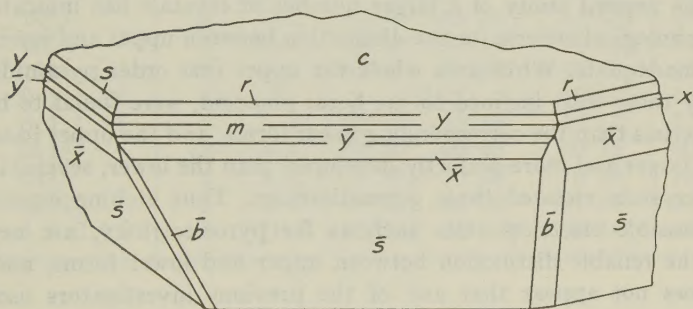
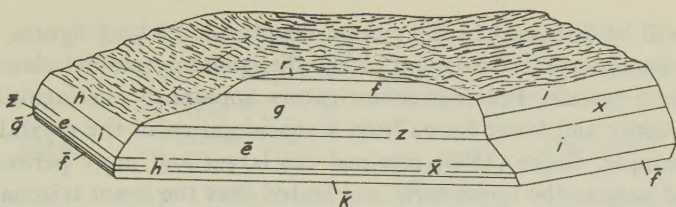


FIG. 1 (top). Alpha (hexagonal) SiC, type I.

FIG. 2 (center). Alpha SiC, type II, showing new second order pyramid, \bar{b} .

FIG. 3 (bottom). Alpha SiC, type III.

As will be discussed in the section devoted to etching figures, type I SiC is hemimorphic, belonging to the ditrigonal-pyramidal class of the hexagonal system. Previous investigators apparently distinguished between upper and lower forms from a consideration of the crystal habit. For example, Becke (1895) retained the larger and more perfectly developed base as the upper form and stated that the lower trigonal pyramids were larger and more numerous, while Peacock (1934) spoke of hemimorphism as evident in the very poor development of the lower trigonal pyramids.

The present study of a larger number of crystals has indicated that morphological criteria for the distinction between upper and lower forms are inadequate. While as a whole the upper first order pyramids, especially those least inclined to the basal pinacoid, were found to be more numerous than the corresponding lower forms, and the upper basal pinacoid larger and more perfectly developed than the lower, several individual crystals violated these generalizations. Thus etching experiments, or possible electrical tests such as for pyroelectricity, are necessary for the reliable distinction between upper and lower forms, and, since it does not appear that any of the previous investigators used such methods for separating these forms, it seems likely that their distinctions between them as indicated in Table 1 were often incorrect, except when faces of both upper and corresponding lower forms occurred on the same crystal. In the present work all distinctions have been made on the basis of differential etching of the basal pinacoids. Form \bar{b} is probably good morphological evidence of hemimorphism, but this form is only present very rarely.

Table 3 contains the morphological data for type I. The axial ratio on which the calculated values and indices are based is that which is indicated by the x -ray study, and gives the greatest simplification of the form indices. Within the limits of error of the measurements, it was found to be rationally related to the very precisely determined $c:a$ value of type II crystals by a factor of $2\frac{1}{2}$, as indicated in Table 8. Table 4 contains an angle table for two-circle goniometry. Insofar as possible, the presentation of the crystallographic data follows the procedure adopted for the new edition of Dana's *System of Mineralogy* as outlined by Wolfe (1941).

Type II. As observed by the previous investigators, crystals of type II were found to be by far the most abundant. The type has been studied in greater detail and the axial ratio more precisely determined than is true of the other types, and it therefore serves as a standard of comparison.

Table 5 gives the morphological data for type II crystals as determined on the one-circle goniometer. Partial data from two-circle measurements

TABLE 3. MORPHOLOGICAL DATA, TYPE I SiC

Form	No. Times Observed	Quality	Angle between Form and Base		
			Measured Range	Weighted Average	Calculated Value
$c\bar{c}$	0001	22	—	—	0°00'
M	1.0.1.13	1	47°30'	47°30'	47°27½'
r	1.0.1.10	2	54°46'	54°46'	54°47'
$f\bar{f}$	1017	13	63°37' - 63°45'	63°42½'	63°42'
$g\bar{g}$	1014	7	74°11' - 74°19'	74°14½'	74°14'
$z\bar{z}$	1011	9	85°51' - 86°02'	85°57½'	85°57½'
\bar{k}	0.1.1.14	1	45°10'	45°10'	45°20'
$h\bar{h}$	0.1.1.11	5	52°10' - 52°13'	52°11'	52°10'
$i\bar{i}$	0118	12	60°30' - 60°40'	60°33'	60°32½'
$x\bar{x}$	0115	6	70°30½' - 70°35'	70°33'	70°33½'
$e\bar{e}$	0112	5	81°52' - 82°00'	81°56'	81°58'
\bar{b}	1.1.2.15	5	58°32½' - 58°36½'	58°34½'	58°33½'

TABLE 4. α -SiC, TYPE I, ANGLE TABLEHexagonal— R ; ditrigonal pyramidal— $3m$

$$a:c = 1:12.267_5$$

$$p_0:r_0 = 14.165_3:1$$

$$\alpha = 13^\circ 54\frac{1}{2}'$$

$$\lambda = 119^\circ 30\frac{1}{2}'$$

Lower	Upper		ϕ	ρ	A_1	A_2
\bar{c}	c	0001	—	0°00'	90°00'	90°00'
	M	1.0.1.13	+30°00'	47°27½'	50°21'	90°00'
	r	1.0.1.10	+30°00'	54°47'	44°58'	90°00'
\bar{f}	f	1017	+30°00'	63°42'	39°04'	90°00'
\bar{g}	g	1014	+30°00'	74°14'	33°33'	90°00'
\bar{z}	z	1011	+30°00'	85°57½'	30°15'	90°00'
\bar{k}		0.1.1.14	-30°00'	45°20'	90°00'	51°59'
\bar{h}	h	0.1.1.11	-30°00'	52°10'	90°00'	46°50½'
\bar{i}	i	0118	-30°00'	60°32½'	90°00'	41°03½'
\bar{x}	x	0115	-30°00'	70°33½'	90°00'	35°15'
\bar{e}	e	0112	-30°00'	81°58'	90°00'	30°57½'
\bar{b}		1.1.2.15	0°00'	58°33½'	64°45'	64°45'

on two crystals showing form \bar{b} , one of which is illustrated by Fig. 2, are included in Table 6. This shows that \bar{b} is a second order pyramid since the ϕ value is 30° from that of the other pyramids which were found to be first order forms.

TABLE 5. MORPHOLOGICAL DATA
TYPE II SiC

Form	No. Times Observed	Quality	Angle between Form and Base		
			Measured Range	Weighted Average	Calculated Values
$c-\bar{c}$ 0001	67	A-B	—	—	0°00'
m 10 $\bar{1}$ 0	26	A-B	89°56' -90°01 $\frac{1}{2}$ '	90°00'	90°00'
$n-\bar{n}$ 10 $\bar{1}$ 5	23	C-D	48°27' -48°40 $\frac{1}{2}$ '	48°33 $\frac{1}{2}$ '	48°34 $\frac{1}{2}$ '
$r-\bar{r}$ 10 $\bar{1}$ 4	17	A-B	54°45' -54°53'	54°47'	54°47'
$s-\bar{s}$ 10 $\bar{1}$ 3	56	A-B	62°03' -62°08'	62°06'	62°06'
$x-\bar{x}$ 10 $\bar{1}$ 2	34	A-B	70°29 $\frac{1}{2}$ ' -70°35 $\frac{1}{2}$ '	70°33 $\frac{1}{2}$ '	70°33 $\frac{1}{2}$ '
$y-\bar{y}$ 10 $\bar{1}$ 1	31	A-B	79°57 $\frac{1}{2}$ ' -80°02 $\frac{1}{2}$ '	79°59 $\frac{1}{2}$ '	79°59 $\frac{1}{2}$ '
\bar{b} 11 $\bar{2}$ 6	5	C-E	58°10' -58°57'	58°37'	58°33 $\frac{1}{2}$ '

TABLE 6. PARTIAL MORPHOLOGICAL DATA, TWO-CIRCLE GONIOMETRY,
TYPE II SiC

Form	No. Times Observed	Quality	Observed, Weighted Averages		Calculated	
			ϕ	ρ	ϕ	ρ
\bar{b} 11 $\bar{2}$ 6	5	C-E	-0°02'*	58°32'	0°00'	58°33 $\frac{1}{2}$ '

* Zone of first order pyramids (+30°00') used as reference.

Etching experiments on a large number of type II individuals likewise proved conclusively that, although this type is hemimorphic, morphological criteria were wholly inadequate to distinguish upper from lower basal pinacoids, except in the rare case when \bar{b} was present.

Although Negri's careful measurements of silicon carbide left little to be desired, axial ratios were calculated from the best observations made on type II crystals during the present investigation. These are contained in Table 7 where a comparison is afforded with the results of Negri and of Espig when the proper transformations have been made. The axial ratio retained, 4.9070, is that which gives the greatest simplification of form indices and the one indicated by x-ray studies.

Table 7 includes measurements on both green and blue black crystals. In order to ascertain whether axial ratios calculated from measurements on green SiC differed from similar calculations on the blue black, $c:a$

TABLE 7. ACCURATE MEASUREMENTS, TYPE II SiC

Form	Excellent Signals		Good Signals		Weighted Average	$c:a$	$c:a$ from Negri (1902)	$c:a$ from Espig (1921)
	Number	Average	Number	Average				
$r-\bar{r}$	5	54°46'03"	12	54°47'25"	54°46'48"	4.9070 ₄	4.9064 ₈	—
$s-\bar{s}$	24	62°06'15"	32	62°05'43"	62°06'01"	4.9069 ₆	4.9070 ₄	—
$x-\bar{x}$	11	70°33'38"	23	70°33'19"	70°33'28"	4.9068 ₈	4.9066 ₄	4.9074 ₈
$y-\bar{y}$	7	79°59'09"	24	79°59'40"	79°59'29"	4.9071 ₆	4.9074 ₄	—
				Weighted Average		4.9070	4.9069	

TABLE 8. OBSERVED AND CALCULATED AXIAL RATIOS, α -SiC TYPES

α -SiC type	Quality and Number of Observed Faces					Observed $c:a$	$c:a$ Calculated from Type II Observed Value	Per Cent Difference
	Excel- lent	Good	Fair	Poor	Very Poor			
II	47	91	—	—	—	4.9070	—	—
II, green	22	52	—	—	—	4.9073	4.9070	+ .006
II, blue-black	25	39	—	—	—	4.9066	4.9070	— .008
I	11	30	20	—	—	12.266 ₇	12.267 ₅	— .007
III	4	7	11	2	2	3.2713	3.2713	none
IV	1	10	10	3	0	17.189 ₇	17.174 ₆	+ .089
VI	3	22	14	6	2	26.982	26.989	— .026
I (from Negri)	(total of 428 of all qualities)					12.269 ₇	12.267 ₅	+ .018
III (from Negri)	(total of 15 of all qualities)					3.2708	3.2713	— .015

values were determined for each of these two varieties. These are included in Table 8. Although the ratios differ by seven units in the fourth decimal place, this is well within the probable limit of error for the number of angles measured and the rather high $c:a$ value.

TABLE 9. ALPHA SiC, TYPE II ANGLE TABLE

Hexagonal— P ; dihexagonal pyramidal— $6mm$.
 $a:c=1:4.9070$ $\rho_0:r_0=5.6661:1$

Lower	Upper		ϕ	ρ	M	A ₂
\bar{c}	c	0001	—	0°00'	90°00'	90°00'
	m	10 $\bar{1}0$	+30°00'	90°00'	60°00'	90°00'
\bar{n}	n	10 $\bar{1}5$	+30°00'	48°34 $\frac{1}{2}$ '	67°59'	90°00'
\bar{r}	r	10 $\bar{1}4$	+30°00'	54°47'	65°53 $\frac{1}{2}$ '	90°00'
\bar{s}	s	10 $\bar{1}3$	+30°00'	62°06'	63°46 $\frac{1}{2}$ '	90°00'
\bar{x}	x	10 $\bar{1}2$	+30°00'	70°33 $\frac{1}{2}$ '	61°52'	90°00'
\bar{y}	y	10 $\bar{1}1$	+30°00'	79°59 $\frac{1}{2}$ '	60°30'	90°00'
\bar{b}		11 $\bar{2}6$	0°00'	58°33 $\frac{1}{2}$ '	90°00'	64°45'

An angle table for two-circle goniometry is given in Table 9.

Type III. The third most common form of α -SiC is designated type III. Although more numerous in previous investigations, only two crystals were found in the course of the present study. The larger, black in color, is illustrated by Fig. 3; the other, about 1 $\frac{1}{2}$ mm. in diameter, contained five faces of the form \bar{b} . Table 10 gives the morphological data, and Table 11 an angle table for the type. The axial ratio indicated by x-ray study yields the greatest simplification of form indices. Crystal measurement shows it to be 3.2713, which is precisely two thirds of the c value determined for type II crystals.

Type IV. Two entirely new types of hexagonal SiC were observed during the course of this study. One, represented by a single large yellow-green crystal, is designated α -SiC, type IV, and is illustrated by Fig. 4.

When this crystal was measured on the goniometer, it was immediately evident that it did not belong to any of the SiC types previously mentioned. Although, like type I, the specimen showed rhombohedral-like face development, it was characterized by an entirely different suite of trigonal pyramids only one of which was apparently equivalent to a type I form. An axial ratio was sought which would simplify the indices of the forms to the greatest extent and at the same time yield simple arithmetical series characteristic of crystals with rhombohedral lattices. When these conditions were fulfilled, the observed $c:a$ value was found to be 17.1897, a ratio which was later substantiated by x-ray study and

which, within the limits of error of the measurements, is $3\frac{1}{2}$ times that precisely determined for type II crystals.

TABLE 10. MORPHOLOGICAL DATA
TYPE III SiC

Form	No. Times Observed	Quality	Angle between Form and Base		
			Measured Range	Weight- ed Average	Calcu- lated Value
<i>c</i> 0001	1	A	—	—	0°00'
\bar{c} 0001	1	A	—	—	0°00'
<i>m</i> 1010	5	A-B	89°57' -90°00 $\frac{1}{2}$ '	89°59 $\frac{1}{2}$ '	90°00'
<i>d</i> 1013	5	C-E	50°53' -51°34'	51°29'	51°32 $\frac{1}{2}$ '
<i>s</i> 1012	6	A-C	62°05' -62°08'	62°07'	62°06'
\bar{s} 1012	5	A-D	62°04 $\frac{1}{2}$ ' -62°11'	62°07'	62°06'
<i>l</i> 1011	5	B-C	75°06' -75°12'	75°10'	75°10 $\frac{1}{2}$ '
\bar{l} 1011	3	A-C	75°09 $\frac{1}{2}$ ' -75°11'	75°10 $\frac{1}{2}$ '	75°10 $\frac{1}{2}$ '
<i>b</i> 1124	5	D-E	58°32' -58°35 $\frac{1}{2}$ '	58°33'	58°33 $\frac{1}{2}$ '

TABLE 11. α -SiC, TYPE III, ANGLE TABLE

Hexagonal—*P*; dihexagonal pyramidal—6mm.
 $a:c=1:3.2713$ $p_0:r_0=3.7774:1$

Lower	Upper		ϕ	ρ	M	A ₂
\bar{c}	<i>c</i>	0001	—	0°00'	90°00'	90°00'
	<i>m</i>	1010	+30°00'	90°00'	60°00'	90°00'
	<i>d</i>	1013	+30°00'	51°32 $\frac{1}{2}$ '	66°57'	90°00'
\bar{s}	<i>s</i>	1012	+30°00'	62°06'	63°46 $\frac{1}{2}$ '	90°00'
\bar{l}	<i>l</i>	1011	+30°00'	75°10 $\frac{1}{2}$ '	61°05 $\frac{1}{2}$ '	90°00'
<i>b</i>		1124	0°00'	58°33 $\frac{1}{2}$ '	90°00'	64°45'

Table 12 gives the morphological data and Table 13 an angle table for the type.

Type V. Type V SiC is reserved for the modification with 51 formula weights per unit cell which has been reported by Ott (1928) on the basis of *x*-ray measurements. A morphological study of the crystal could not be made by Ott because all pyramids had been broken from the thin tabular piece. No crystal of this type was encountered during the present study, but in view of the new types IV and VI with rather high *c:a* values and large number of formula weights per unit cell, type V is not at all improbable.

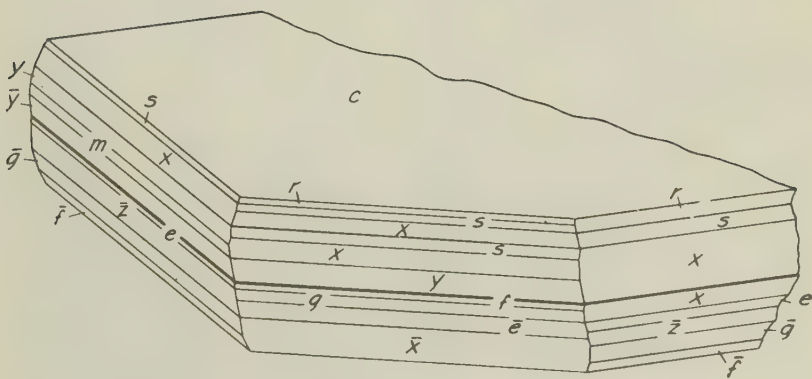
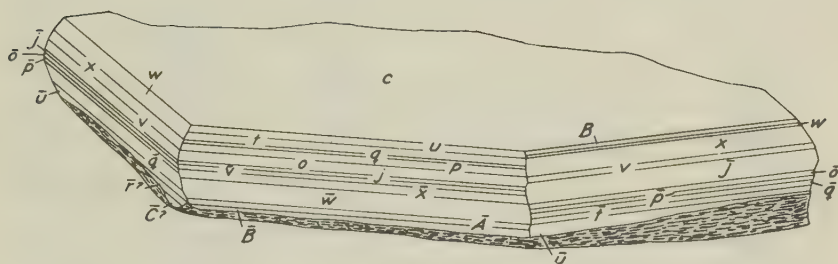
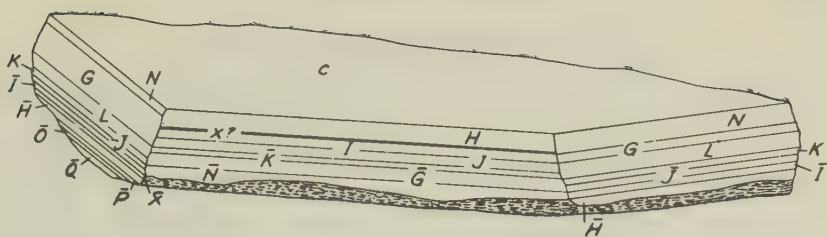


FIG. 4 (top). Alpha SiC, type IV.

FIG. 5 (center). Alpha SiC, type VI.

FIG. 6 (bottom). Coalescence of alpha SiC, type II (above), with type I (below).

TABLE 12. MORPHOLOGICAL DATA
TYPE IV SiC

Form	No. Times Ob- served	Quality	Angle between Form and Base		
			Measured Range	Weighted Average	Calcu- lated Value
c 0001	1	A	—	—	0°00'
\bar{c} 0001	1	C	—	—	—
\bar{Q} 0.1.1.19	1	D	46°13½'	46°13½'	46°13½'
\bar{O} 0.1.1.16	1	C	51°04½'	51°04½'	51°06'
\bar{P} 0.1.1.13	1	B	56°46'	56°46'	56°45'
H 1.0.1.10	1	B	63°19'	63°19'	63°14½'
\bar{H} 0.1.1.10	2	C	63°03' - 63°15½'	63°09½'	
\bar{x} 0117	1	C	70°41'	70°41'	70°33½'
I 1014	1	C	78°41'	78°41'	
\bar{I} 0114	2	C-D	78°32' - 79°03'	78°47½'	78°36'
J 1011	1	B	87°11'	87°11'	87°07'
\bar{J} 0111	2	C-D	87°16' - 87°26'	87°21'	
N 0.1.1.11	2	B	61°03' - 61°09½'	61°06½'	60°59'
\bar{N} 1.0.1.11	2	B	60°54½'	60°54½'	
G 0118	2	B-C	67°59' - 68°06'	68°02½'	68°02'
\bar{G} 1018	1	B	67°51½'	67°51½'	
L 0115	2	A-B	75°51½' - 75°52'	75°52'	75°51'
K 0112	2	C	83°44' - 83°57'	83°50½'	
\bar{K} 1012	1	B	84°12½'	84°12½'	84°14½'

TABLE 13. α -SiC, TYPE IV, ANGLE TABLEHexagonal— R ; ditrigonal pyramidal— $3m$

$$a:c = 1:17.174_5$$

$$\alpha = 9^\circ 58'$$

$$p_0:r_0 = 19.831_4:1$$

$$\lambda = 119^\circ 45'$$

Lower	Upper		ϕ	ρ	A_1	A_2
\bar{c}	c	0001	—	0°00'	90°00'	90°00'
\bar{Q}		1.0.1.19	+30°00'	46°13½'	51°17½'	90°00'
\bar{O}		1.0.1.16	+30°00'	51°06'	47°37½'	90°00'
\bar{P}		1.0.1.13	+30°00'	56°45'	43°35½'	90°00'
\bar{H}	H	1.0.1.10	+30°00'	63°14½'	39°21'	90°00'
\bar{x}		1017	+30°00'	70°33½'	35°15'	90°00'
\bar{I}	I	1014	+30°00'	78°36'	31°54'	90°00'
\bar{J}	J	1011	+30°00'	87°07'	30°07½'	90°00'
\bar{N}	N	0.1.1.11	-30°00'	60°59'	90°00'	40°46½'
\bar{G}	G	0118	-30°00'	68°02'	90°00'	36°34'
	L	0115	-30°00'	75°51'	90°00'	32°53'
\bar{K}	K	0112	-30°00'	84°14½'	90°00'	30°30'

Type VI. Figure 5 illustrates a large black SiC crystal showing rhombohedral-like face development with different series of forms in alternate trigonal pyramid zones. These series, however, were entirely unlike those of any of the other α -SiC types, only the basal pinacoid and the first order pyramids r and $x\bar{x}$ being equivalent to forms found on the other types.

Again an axial ratio was sought which would offer the greatest simplification of form indices, yield simple arithmetical series of forms characteristic of crystals with rhombohedral lattices and at the same time be rationally related to the observed $c:a$ value for type II crystals. A ratio $5\frac{1}{2}$ times that of type II was found to satisfy these requirements; later the ratio was substantiated by x-ray study. Table 8 indicates that, within the limits of error of the measurements, the axial ratio is truly rationally related to that of type II.

TABLE 14. MORPHOLOGICAL DATA, TYPE VI SiC

Form	No. Times Observed	Quality	Angle between Form and Base		
			Measured Range	Weighted Average	Calculated Value
c 0001	1	A	—	—	0°00'
C 1.0.1.28	2	B	48°00'–48°02½'	48°01½'	48°03½'
r 1.0.1.22	2	A–B	54°42'–54°46'	54°44'	54°47'
u 1.0.1.16	3	B–C	62°48'–62°51'	62°49½'	62°40½'
\bar{u} 0.1.1.16	2	B	62°45'–62°47½'	62°46½'	
t 1.0.1.13	2	B–D	66°54'–67°24'	67°14'	67°21½'
\bar{t} 0.1.1.13	1	B	67°24'	67°24'	
q 1.0.1.10	3	C–E	71°44½'–72°20'	72°14'	72°12½'
\bar{q} 0.1.1.10	2	A–B	72°12½'–72°14'	72°13½'	
p 1017	1	C	77°20'	77°20'	77°20½'
\bar{p} 0117	2	B–C	77°17½'–77°23'	77°20½'	
o 1014	1	B	82°43'	82°43'	82°41'
\bar{o} 0114	2	B	82°42'–82°44'	82°43'	
j 1011	1	B	88°10½'	88°10½'	88°09½'
\bar{j} 0111	2	A–D	87°47'–88°11'	88°04'	
D 0.1.1.26	1	B	50°09'	50°09'	50°09½'
B 0.1.1.23	2	C–E	53°28½'–53°33'	53°32'	53°34½'
\bar{B} 1.0.1.23	3	C–D	53°38'–53°40½'	53°39'	
\bar{A} 1.0.1.20	2	D	57°18½'–57°20½'	57°19½'	57°18½'
w 0.1.1.17	3	B–C	61°22½'–61°23'	61°22½'	
\bar{w} 1.0.1.17	3	B–C	61°18½'–61°30½'	61°24'	61°23'
x 0.1.1.11	3	B–D	70°33'–70°37'	70°34'	
\bar{x} 1.0.1.11	1	B	70°33½'	70°33½'	70°33½'
v 0115	2	C	80°51½'–80°55½'	80°53½'	
\bar{v} 1015	1	C	80°52'	80°52'	80°53'

TABLE 15. α -SiC, TYPE VI, ANGLE TABLEHexagonal—*R*; ditrigonal pyramidal— $3m$

$$a:c=1:26.989$$

$$\alpha=6^{\circ}21\frac{1}{2}'$$

$$p_0:r_0=31.164:1$$

$$\lambda=119^{\circ}54'$$

Lower	Upper		ϕ	ρ	A_1	A_2
	c	0001	—	0°00'	90°00'	90°00'
	C	1.0.1.28	+30°00'	48°03 $\frac{1}{2}$ '	49°54'	90°00'
	r	1.0.1.22	+30°00'	54°47'	44°58'	90°00'
\bar{u}	u	1.0.1.16	+30°00'	62°49 $\frac{1}{2}$ '	39°36 $\frac{1}{2}$ '	90°00'
\bar{l}	l	1.0.1.13	+30°00'	67°21 $\frac{1}{2}$ '	36°56 $\frac{1}{2}$ '	90°00'
\bar{q}	q	1.0.1.10	+30°00'	72°12 $\frac{1}{2}$ '	34°27'	90°00'
\bar{p}	p	1017	+30°00'	77°20 $\frac{1}{2}$ '	32°20'	90°00'
\bar{o}	o	1014	+30°00'	82°41'	30°48'	90°00'
\bar{j}	j	1011	+30°00'	88°09 $\frac{1}{2}$ '	30°03'	90°00'
	D	0.1.1.26	—30°00'	50°09 $\frac{1}{2}$ '	90°00'	48°19 $\frac{1}{2}$ '
\bar{B}	B	0.1.1.23	—30°00'	53°34 $\frac{1}{2}$ '	90°00'	45°49 $\frac{1}{2}$ '
\bar{A}		0.1.1.20	—30°00'	57°18 $\frac{1}{2}$ '	90°00'	43°12 $\frac{1}{2}$ '
\bar{w}	w	0.1.1.17	—30°00'	61°23'	90°00'	40°31'
\bar{x}	x	0.1.1.11	—30°00'	70°33 $\frac{1}{2}$ '	90°00'	35°15'
\bar{v}	v	0115	—30°00'	80°53'	90°00'	31°14'

Table 14 gives the morphological data for type VI, while an angle table is included in Table 15.

Relationship of Types. It will be even more evident after the *x*-ray and optical data have been considered that the types are not merely different habits of hexagonal SiC, nor do they, on the other hand, represent modifications with entirely separate physical and optical properties, such as shown by the usual polymorphic substances of which calcite and aragonite may be taken as examples. In view of these relationships all the hexagonal modifications are now referred to as α -SiC, the types being designated by Roman numerals. Following Baumhauer, the phenomenon is called "polytypism" the adjective being "polytypic" and each one of the different modifications a "type." On the other hand, the cubic modification differs in crystal system and optical properties as would be expected of the usual dimorphic substances, sphalerite and wurtzite, for example, and is here designated β -SiC.

Although the axial ratios to which each of the types has been referred afford the greatest simplification of first order pyramid forms, this is not the case with the second order pyramid \bar{b} . If the greatest common divisor of the accepted $c:a$ ratios of the various types, 0.8178, be chosen as the axial ratio of all the modifications and Bravais indices then calculated from it, the relationships among the types and among the various forms are evident in the remarkable manner indicated in Table 16. Here

in the vertical columns are the upper forms of the various α -SiC types and the Bravais indices calculated from $c = 0.8178$. This new method of notation shows that in the case of the first order pyramids the first and third or the second and third numerals of the indices are exactly the number of formula weights in the unit cells of the respective SiC types, and that the only forms which are common to two or more modifications are those forms whose indices are equivalent when referred to this greatest common divisor $c:a$ value. The table also shows that the greatest simplification of the second order pyramid is obtained by this treatment. These relationships would seem to indicate that 0.8178 is the "axial ratio" of one "molecule" of SiC which is common to all the α -SiC types.

COALESCENCE OF TYPES

The crystals thus far considered contained forms which were consistent throughout with one of the SiC types, but this was not usually the case. Figure 6 illustrates a broken but otherwise well-developed individual which actually consists of two portions; all the faces adjacent to the upper base are those of type II, while those adjacent to the lower base belong to type I. In this crystal the contact between the two types is clearly a plane which is parallel to the basal pinacoids; it is indicated on the figure by the heavy line. The outcrop of this contact on the fractured portion of the crystal is marked by a fine striation. Figure 6 thus indicates a coalescence of types I and II with common c and a axes such that the resulting mass is indistinguishable under the stereoscopic microscope from a crystal composed entirely of one type. It should be pointed out that in one zone face x is common to both types involved in the coalescence. This is possible since the form is one of those occurring in both SiC types.

Other examples found during the course of this study, in addition to the numerous cases cited by Baumhauer (1915) clearly indicate that any combination of types may coalesce in the manner described and illustrated above. It would undoubtedly be found that SiC crystals which show multitudes of small re-entrant angles and striae consist of thin plates of several of the types, or oscillations between two or more of them.

Ungemach (1935*b*) has introduced the term *syntaxie* to describe the coalescence of polytypic substances as illustrated above with the SiC types. The best English equivalent is probably "syntaxis," the adjective being "syntactic."

In addition to this intimate and special method of contact between the various types, there are others. Crystals which are of one type throughout, for example, may appear adjacent to individuals entirely of another type, either as parallel growths or as intergrowths with no common planes, or as indicated below, twinning may involve two or more types.

TABLE 16. CORRELATION OF FORMS ON α -SiC TYPES, INDICES REFERRED TO $c:a=0.8178$
 α -SiC TYPES

I	IV	VI	II	III
c 0001	c 0001	c 0001	c 0001	c 0001
M 15.0. $\overline{15}$.13		C 33.0. $\overline{33}$.28	m 6060 (10 $\overline{10}$) n 6065	m 4040 (10 $\overline{10}$) d 4043
r 15.0. $\overline{15}$.10 (30 $\overline{32}$)	*	r 33.0. $\overline{33}$.22 (30 $\overline{32}$)	r 6064 (30 $\overline{32}$)	
f 15.0. $\overline{15}$.7 g 15.0. $\overline{15}$.4 z 15.0. $\overline{15}$.1	N 0.21. $\overline{21}$.11 G 0.21. $\overline{21}$.8 L 0.21. $\overline{21}$.5 K 0.21. $\overline{21}$.2	u 33.0. $\overline{33}$.16 t 33.0. $\overline{33}$.13 q 33.0. $\overline{33}$.10 p 33.0. $\overline{33}$.7 o 33.0. $\overline{33}$.4		
k 0.15. $\overline{15}$.14 h 0.15. $\overline{15}$.11 i 0.15. $\overline{15}$.8	Q 21.0. $\overline{21}$.19 O 21.0. $\overline{21}$.16 P 21.0. $\overline{21}$.13 H 21.0. $\overline{21}$.10	j 33.0. $\overline{33}$.1 D 0.33. $\overline{33}$.26 B 0.33. $\overline{33}$.23 A 0.33. $\overline{33}$.20 w 0.33. $\overline{33}$.17	s 6063 (20 $\overline{21}$)	s 4042 (20 $\overline{21}$)
x 0.15. $\overline{15}$.5 (03 $\overline{31}$)	x 21.0. $\overline{21}$.7 (30 $\overline{31}$)	x 0.33. $\overline{33}$.11 (03 $\overline{31}$)	x 6062(30 $\overline{31}$) = (03 $\overline{31}$)	
e 0.15. $\overline{15}$.2	I 21.0. $\overline{21}$.4 J 21.0. $\overline{21}$.1	v 0.33. $\overline{33}$.5	y 6061	l 4041
b 11 $\overline{21}$	*	*	b 11 $\overline{21}$	b 11 $\overline{21}$

* Not observed but of possible occurrence from theoretical considerations.

TWINNING

The most readily observed and probably the most frequent twinning arrangement involving α -SiC is that reported upon by previous investigators, namely, that in which the basal pinacoids of the twinned individuals are inclined to each other an average of about $70^{\circ}36'$ (obtuse angle as measured on the goniometer). The lines of contact between the individuals, which are usually tabular, are at the same time parallel to edges of the basal pinacoids of each of the portions involved in the twin. In certain areas on some lumps of crude SiC this type of twinning affects almost all of the crystals. Here repeated twinings and parallel growths are common.

In an attempt to distinguish between the two possible twinning arrangements suggested by Becke, careful determinations of the obtuse angle between the basal pinacoids were made on fifty twins of this nature chosen at random. The only twins accepted for measurement were those whose basal pinacoids adjacent to the obtuse angle afforded signals which were single and of excellent quality.

In spite of the fact that each angle is probably accurate to within $\pm 1'$, it is of particular interest to note that the observed twinning angle varied from $70^{\circ}25'$ to $70^{\circ}44'$, a range of $19'$, and that the maximum number of observations at any one angular value was 6. For comparison, the angles between the pyramids s or \bar{s} and the nearest basal pinacoid of type II crystals were also measured in fifty cases at random. In spite of the lower expected accuracy of the individual readings, they varied from $62^{\circ}03'$ to $62^{\circ}08'$, or a range of only $5'$, with 26 of the angles at the one value of $62^{\circ}06'$. Eighty-eight per cent of the angles fell within $\pm 1'$ of the average, while with the case of the twins only 30% fell within this limit. These data indicate that this type of twinning in α -SiC is to be classed with parallel growths as an arrangement of individuals according to a law which is only approximately satisfied. It also explains why Becke's value for the axial ratio of SiC differs greatly from that of all other investigators (see Table 1). His value was calculated from twinning angles, while all other axial ratios were determined from interfacial angles on single crystals.

The average of the fifty observed twinning angles is $70^{\circ}35'55''$; this compares with $70^{\circ}33'10''$, the weighted average of published values on eight crystals. If the twinning satisfied the law: twinning axis perpendicular to the form r , as suggested by previous investigators, the calculated twinning angle would be $70^{\circ}26'24''$, which is lower than all but one of the fifty twins included in the study mentioned above. If the twinning plane were the possible form E (see Table 2), the calculated angle would be

$70^{\circ}37'02''$. The closer accord with the latter value might suggest this twinning law, but it is difficult to believe that the twinning is related to the complex plane E in preference to the simpler and very fundamental plane r .

In the following section on cubic SiC it will be shown that in one crystal of this substance there exist two very thin plates of α -SiC which are parallel to adjacent faces of the positive and negative tetrahedrons. These two α -SiC plates are thus inclined to one another $70^{\circ}31\frac{3}{4}'$, the octahedral angle. Since cubic SiC may be a low-temperature form which, according to Tone (1938), reverts to hexagonal SiC at an elevated temperature, it is possible that the octahedral angle might be preserved should any α -SiC twin have grown from inclusions of α -SiC in the cubic modification as described above. This possibility should be investigated experimentally before any opinion is expressed concerning the twinning law involving the individuals described above.

Eight twins were examined in detail for hexagonal SiC types involved. The most common twin of the nature described above contained individuals of type II as illustrated by Fig. 7. In one case types I and II were twinned, and in three cases individuals of type II were twinned with syntactic intergrowths of types I and II.

Another twinning arrangement was observed which involved only type I α -SiC. It is illustrated by the clinographic projection, Fig. 8, as well as by the diagram of etching figures, Fig. 10. It will be shown in the section devoted to etching that the twinning law represented here is: twinning axis, the c crystallographic axis. Although only two examples of this twinning law were encountered during the study, it is probable that it is more common in the more complex syntactic intergrowths accompanied by highly striated faces. It is also probable that the twinings described by Baumhauer and by Espig as: twinning plane parallel to the base, were in reality twinned around the c axis since these authors apparently made no experiments which were capable of distinguishing between the two possibilities. Certainly in the course of etching over a hundred α -SiC crystals during the present study nothing was observed which would indicate that the basal pinacoid was a twinning plane.

BETA SiC

Practically all samples of sized commercial silicon carbide contain less than about five per cent of particles which are either entirely isotropic, or are partially isotropic containing lamellae of anisotropic material, as is fully described in the section on optical properties.

Examination of a "pig" of SiC from the usual resistance type furnace of intermittent operation revealed a concentration of this isotropic con-

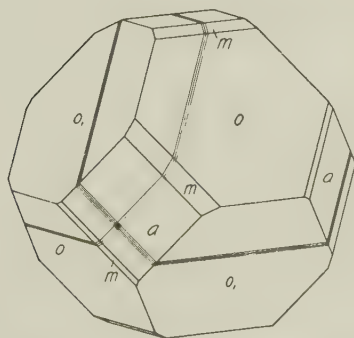
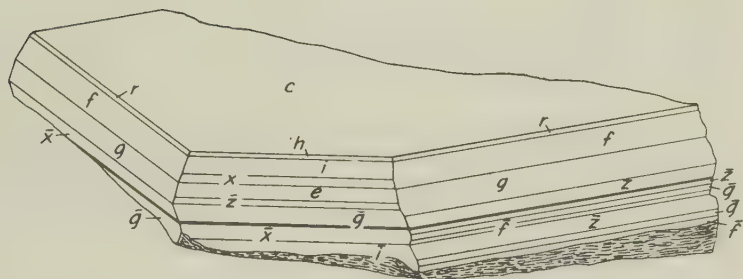
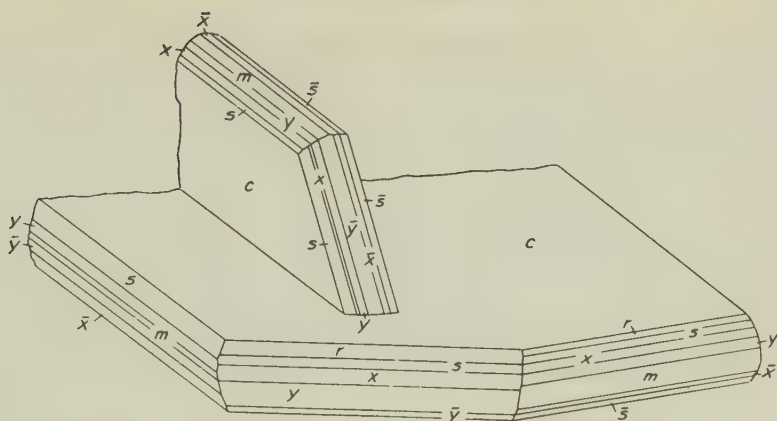


FIG. 7 (top). Most common twinning arrangement of alpha SiC. Type II twinned with type II.

FIG. 8 (center). Alpha SiC, type I, twinned with type I. Twinning axis: c crystallographic axis.

FIG. 9 (bottom). Beta (cubic) SiC. Striations indicate outcrops of included plates of alpha SiC.

stituent in the zones containing very finely crystalline SiC and "fire-sand." These occur between the area of closely intergrown larger crystals and masses of α -SiC toward the hotter core of the furnace, and the cooler zone of partially converted to unconverted material toward the outside of the "pig." Even in the fine crystalline and "firesand" zones, however, the isotropic substance was a very minor constituent, most of the material being α -SiC with small amounts of carbon and other impurities.

Most of the isotropic substance was present as tiny irregular to rounded individuals less than $\frac{1}{2}$ mm. in size, sometimes occurring alone, but more often in the form of very finely granular aggregates showing multitudes of minute crystal faces, or associated with single or twinned crystals or aggregates of α -SiC.

Several essentially isotropic individuals were sufficiently well developed for measurement on the one-circle goniometer. One of these crystals, illustrated by Fig. 9, although only 0.27 mm. in its largest diameter, was exceptionally well developed and only slightly distorted. Transparent, olive green in color, it was practically complete and showed no apparent point of attachment to other crystals. The forms observed under the high power of a stereoscopic microscope were six faces of the cube, four each of the positive and negative tetrahedrons, and ten, possibly eleven, of a positive trigonal tristetrahedron which goniometric measurements proved to be the form $m(113)$. No faces of a corresponding negative trigonal tristetrahedron were present.

Other combinations of forms observed were: positive and negative tetrahedrons distorted by elongation parallel to one of the binary axes; a large cube face with smaller positive and negative tetrahedrons; a pseudo-hexagonal combination of cube and positive and negative tetrahedrons.

Table 17 gives the results of goniometric measurements on the four cubic crystals. Because of the extremely small size of the crystals, and hence of the faces, most of the signals were weak and broad. No signal could be obtained from some of the smallest faces although they could be seen under the high powers of a stereoscopic microscope. In spite of the poor signals obtained from these minute faces, the agreement between observed and calculated values is very satisfactory. The presence of ten, possibly eleven, faces of the positive trigonal tristetrahedron $m(113)$ with a complete absence of the corresponding negative form, and the absence of tetartohedral forms would indicate the hextetrahedral class of the isometric system.

The cubic crystal illustrated by Fig. 9, in common with most of the isotropic substance in commercial SiC, contained lamellae of anisotropic material identified as thin basal plates of α -SiC. There were two such

lamellae in this crystal. The outcrops of these on the surface of the crystal were marked by striae which are indicated on the figure. One lamella was parallel to a face of the positive tetrahedron; the second, penetrating the first, was parallel to a face of the negative tetrahedron, the two thus being inclined to each other at about $70^{\circ}32'$. It is important to

TABLE 17. MORPHOLOGICAL DATA, β -SiC

Angle	Number of Readings on Different Angles	Measured Range	Average	Calculated Value
$\alpha(001) \wedge o(111)$ or $\alpha(001) \wedge o_1(\bar{1}11)$	17	$54^{\circ}19' - 55^{\circ}13'$	$54^{\circ}45\frac{1}{4}'$	$54^{\circ}44\frac{1}{4}'$
$o(111) \wedge o_1(\bar{1}11)$	13	$70^{\circ}20' - 70^{\circ}44'$	$70^{\circ}31\frac{1}{2}'$	$70^{\circ}31\frac{3}{4}'$
$\alpha(001) \wedge m(113)$	6	$25^{\circ}00' - 25^{\circ}25'$	$25^{\circ}14\frac{1}{2}'$	$25^{\circ}14\frac{1}{4}'$
$o(111) \wedge m(113)$	7	$29^{\circ}15' - 29^{\circ}33'$	$29^{\circ}27\frac{1}{2}'$	$29^{\circ}29\frac{3}{4}'$

note that within the cubic crystal there were two tabular crystals of α -SiC intergrown in the same manner as the most common α -SiC twins and with similar inclination angle, and that the basal pinacoids of the included α -SiC plates were parallel to tetrahedron faces. The same relationships were observed on associations of the cubic substance and macroscopic crystals of α -SiC. In all cases tetrahedron faces of the cubic material were in contact with basal pinacoids of α -SiC.

Because of these facts and the additional relationships pointed out in the section on x -ray crystallography, there is little doubt that this cubic substance is an entirely different modification of SiC which will be designated β -SiC. A sufficient amount of this material could not be isolated for complete chemical analysis, but a spectroscopic analysis of a sample containing over 50% of the cubic substance, with the remainder α -SiC, was made by Dr. W. J. O'Leary and Mr. W. M. Hazel of the Norton Chippawa laboratories. A large amount of Si, a very small amount of Al and a trace of Mg were found. Because of the use of carbon electrodes the detection of this element in the sample tested was not possible.

In the relationships pointed out above, one of the four diagonal axes of trigonal symmetry in β -SiC is parallel to the c axis of α -SiC. It is not mere coincidence that both of these axes are polar, but an indication of the close structural similarity of the two modifications. The relationships also explain why α -SiC crystals twinned according to the most common law are symmetrical to a plane bisecting the acute re-entrant angle.

ETCHING FIGURES

REVIEW OF LITERATURE

Becke (1895), using a melt of NaNO_3 and Na_2CO_3 to etch SiC crystals, observed that the larger and more perfectly developed base, which he designated the upper basal pinacoid, always remained bright after etching, but contained very small six-sided etching figures having three longer sides alternating with three shorter. At the same time, the lower basal pinacoid was attacked to a greater extent and showed no etching figures. No observations concerning the results of etching on pyramid or prism faces were recorded. As a result of these observations and the evidence from crystal morphology, Becke placed SiC in the ditrigonal-pyramidal class of the hexagonal system, a determination accepted by Groth (1906). Individuals which Becke considered to be twinned on the normal to the form now designated r were symmetrical to a plane bisecting the acute re-entrant angle.

Baumhauer (1915), repeating Becke's etching experiments, was unable to obtain any clear etching figures on any of his newly discovered three types, but did observe that the basal pinacoids were differentially attacked. On a crystal of type II which he had not etched, Baumhauer observed white spots containing equilateral triangles, or two equilateral triangles one turned 60° with respect to the other. This led him to believe that type II was also ditrigonal-pyramidal.

Weigel (1916), using a melt of K_2CO_3 and KNO_3 (2:1) on a type II crystal, observed equilateral hexagons on one basal pinacoid while the other base was quite evenly dulled. Pyramids and the prism in one zone showed modified triangles which were symmetrical to a vertical plane, but which indicated the absence of a horizontal plane of symmetry. Using borax at 1000°C ., Weigel obtained equilateral hexagons on both basal pinacoids of a type II crystal and bisymmetrical rectangular etches on prism faces.

Espig (1921), using a melt of KOH , NaNO_3 and Na_2CO_3 as the etching medium, obtained a six-sided cavity with three longer sides alternating with three shorter on one base of a type I crystal and an equilateral hexagon on one base of a type II crystal. Espig referred type I to the ditrigonal-pyramidal, and type II to the dihexagonal-pyramidal class of the hexagonal system.

Although the etching experiments carried out by these investigators suggest the classes accepted by Espig, the class of type I has not been proven from these data. Moreover, Weigel's description of bisymmetrical etches on the prism of a type II crystal affords contradictory evidence for the dihexagonal-pyramidal class.

ETCHINGS BY FUSION METHODS

Because of the incomplete and inconsistent nature of the published data, a thorough study of etching was undertaken in order to determine the crystal class of each of the available SiC modifications, and the laws governing the twinning.

Crystals of types I and II were etched by all the media described in the literature. In every case, except with the use of borax, results similar to those reported by Espig were obtained, and no figures could be observed on any of the pyramids or prisms.

In order to ascertain whether, as stated by Becke, the larger and more perfectly developed base were the least attacked by a $\text{NaNO}_3\text{-Na}_2\text{CO}_3$ fusion, twelve crystals of undetermined type were selected for study. In each case one base was exceptionally large and perfectly developed, while the other base was very small and imperfect. Ten of the crystals yielded the expected result upon etching, but two were exactly opposite. Apparently Becke's generalization was based on too few observations, for it is impossible to correctly determine which is the upper and which the lower base without carefully etching each crystal, or detecting polarity by some electrical method.

Excellent etches were obtained by employing a borax fusion at red heat for a duration of 1–2 hours. Iron crucibles were used throughout this study since they were found to have sufficient life if carefully treated. Within the area defined by the dotted lines, Figure 10 shows in a diagrammatic manner the etches observed on type I α -SiC. Only mature figures of definite forms are included in the diagram which does not attempt to indicate the relative size or frequency of the etches, nor the size or shape of the crystal faces. The shape and distribution of the figures indicate three vertical planes of symmetry bisecting the first order pyramids, and a vertical axis of three-fold symmetry. The absence of a horizontal plane and center of symmetry is indicated by differential etching of the bases as well as by entirely differently shaped figures on similar pyramids at opposite ends of the crystal. .

Figure 10 shows the etching figures obtained by the use of borax on the type I twin illustrated by Fig. 8. In Figure 10, the heavy lines between certain crystal faces indicate the position of the prism which, however, does not occur in type I; the dotted line indicates the position of the composition plane of the twin. Since type I SiC has a vertical axis of three-fold symmetry and lacks a center of symmetry, the twinning law could be either: (1) twinning plane (0001), or (2) twinning axis parallel to the c crystallographic axis. Neither morphological nor x -ray study is capable of answering the question, but a study of the etching arrangement indicates that the latter is the correct twinning law.

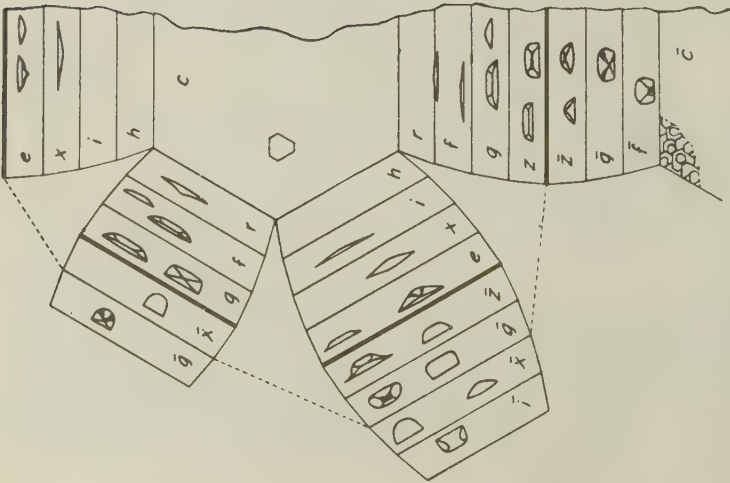


FIG. 10. Etching figures obtained by fused borax on the alpha SiC, type I, twin illustrated by Fig. 8. Dotted line indicates composition plane of twin.

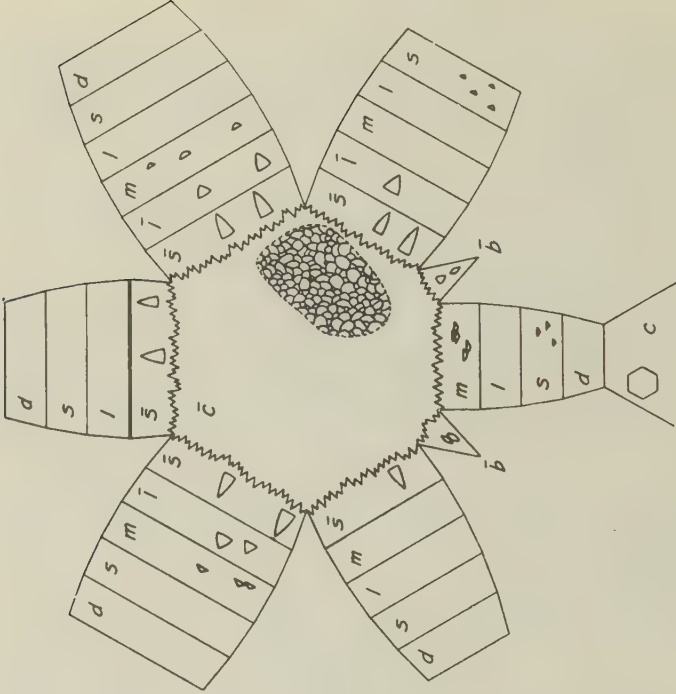


FIG. 11. Etching figures obtained on alpha SiC, type III, by Cl₂ at 1000° C.

Except that the hexagons formed on the one basal pinacoid were equilateral, the etching figures developed by fused borax on α -SiC, type II, were very similar in general appearance to those on type I. A vertical axis of six-fold symmetry and at least three vertical planes of symmetry were present, while a horizontal plane and center of symmetry were absent. The prism faces *m* contained etches devoid of a horizontal plane of symmetry although some of them, especially when not fully mature, were nearly the bisymmetrical rectangles reported by Weigel.

Because of the small number of type III crystals available, none was etched with borax.

Small portions chipped from α -SiC, types IV and VI, were etched by the borax method. The etching figures were very similar to those obtained on type I and the same symmetry elements are indicated.

Twenty-four examples of individuals twinned according to the most common method were etched by the Na_2CO_3 - NaNO_3 fusion method. Green and black crystals from several sources, both domestic and foreign, were included, but in all cases the twinned individuals were symmetrical to a plane bisecting the acute re-entrant angle, as observed by Becke.

ETCHINGS BY CHLORINE

Moissan (1893) stated that SiC was completely decomposed by a current of Cl_2 at about 1200°C . The substance is progressively attacked with volatilization of Si as SiCl_4 , leaving a carbon pseudomorph which may also be removed by reaction with O_2 or air at elevated temperatures forming CO_2 . It was found that a partial chlorination of suitable SiC crystals followed by a removal of the carbon by burning in air produced excellent well-defined etching figures very different in appearance from those formed by the borax fusion.

In the apparatus used for the etching, Cl_2 from the usual pressure cylinder was forced through a bubble tower partially filled with concentrated H_2SO_4 , into a fused silica tube of about one inch diameter, exit being made by rubber tubing to the outdoors. A gas-tight joint in one end of the fused silica tube permitted insertion of a fused silica boat containing the crystals to be etched. An electric furnace, cylindrical in shape with the upper half removable, entirely enclosed the central portion of the silica tube and permitted the enclosed boat with contents to reach a maximum temperature of 1000 – 1050°C ., at which temperature the etching experiments with Cl_2 were carried out. When chlorination of the crystals was judged sufficient, the Cl_2 was replaced by compressed air which removed the carbon remaining from the chlorination. In all the experiments the apparatus was operated by Mr. F. M. Fellows.

Figure 11 illustrates diagrammatically the type of etches obtained by

the Cl_2 method. In every case, whether with $\alpha\text{-SiC}$, types I, II or III, all of which were etched by this method, one basal pinacoid was very badly attacked, usually with the formation of isolated or grouped etch hillocks of modified conical shape. These were largely confined to the edges of the basal pinacoid so that when the crystal was viewed from the side, the contact between the base and the adjacent pyramid was saw-toothed as indicated in Fig. 11. The other basal pinacoid was in all cases only slightly attacked, and contained very well-defined etching figures similar to those produced by borax.

First order pyramids adjacent to the lower base contained well-defined triangles with apices pointing toward the upper base, while corresponding upper first order pyramids showed no etching figures, or, at most, tiny poorly-defined triangles with apices pointing in the same direction. Etches obtained on prism faces indicated the absence of a horizontal plane of symmetry.

Several crystals containing the second order pyramid, \bar{b} , were etched by the Cl_2 method, but only in the case of the type III crystal, Fig. 11, were any well-defined etches observed on these extremely minute faces. The etches observed in this case were symmetrical to a vertical plane.

Seven large crystals of types I and II were sawed in half parallel to the c axis. One-half of each crystal was etched with Cl_2 . The second half of four crystals was etched with borax, and the second half of the remaining three was etched with the $\text{Na}_2\text{CO}_3\text{-NaNO}_3$ melt. The basal pinacoid attacked to the greatest extent by the Cl_2 was also attacked most by the other etching media, and has arbitrarily been chosen the lower base in the present study.

Because of the extremely small size of all available crystals of $\beta\text{-SiC}$, no attempts were made to obtain etching figures on them.

The etching figures developed on $\alpha\text{-SiC}$, types I, IV and VI, both by fused borax and by Cl_2 at 1000°C ., admit of but one interpretation as to crystal class, namely, ditrigonal-pyramidal, or $3m$ of the hexagonal system, while types II and III are to be referred to the dihexagonal-pyramidal, or $6mm$ class of the same system.

(To be continued)

WHITE MICA IN THE WISSAHICKON COMPLEX

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ABSTRACT

The white mica described has unusual optical properties. The values of $2V$ are lower than those reported in the literature, and do not correlate with values that would be expected from the indices of refraction.

Information is given on the origin of the mica. Discussion and interpretation is further based on optical data, a Laue x -ray photograph, and chemical composition.

INTRODUCTION

The junior author, in the course of investigating the granitic rocks in the Wissahickon Valley (1), reported a white mica with unusually small optic axial angle. J. Berman (2) had previously called attention to a similar though rare mica from another locality in the Philadelphia area. The material in the Wissahickon Valley occurs in crystals sufficiently numerous and large enough to permit easy collection and concentration.

The mica studied was collected in the valley of the Wissahickon Creek, a few hundred feet south of the contact between the Wissahickon formation and the mylonite member of the Baltimore gneiss. The white mica is found in the granitic rock and also in the adjacent Wissahickon schist. The mineral is best seen, however, in the granitic rock which is well exposed in an abandoned quarry on the west bank of the Wissahickon Creek. The granitic rock is a dike-like mass surrounded by the Wissahickon formation; it may be seen in Armstrong's (3) recent map, or in the older map of Bascom (4).

ACKNOWLEDGMENTS

Thanks are due Dr. P. H. Miller, Jr., of the Physics Department of the University of Pennsylvania for making several Laue photographs of the mica. The chemical analysis was made possible by a grant from the Faculty Research Committee of the University of Pennsylvania. Appreciation is expressed to Professor E. S. Larsen of Harvard University for technical advice, and for critical reading of the manuscript; also to Dr. Dorothy Wycoff of Bryn Mawr College for her interest and valuable suggestions.

FIELD DESCRIPTION OF THE HOST ROCKS

Wissahickon Formation

The Wissahickon rock at the contact with the dike is a moderately coarse, well foliated mica schist. Associated with the coarse schist and

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alternating with it, parallel to the plane of the schistosity, is a fine-grained quartzitic biotite schist. In this latter facies the biotite is sparsely distributed through the rock and is aligned parallel to the regional strike of the foliation. The schists in the vicinity of the granitic dike have crystals of black tourmaline arranged parallel to the foliation. The largest tourmaline crystals measure 1 mm. by 3 mm.

The schistosity of the Wissahickon formation has an average strike of N. 60° E. and an average dip of 80° to the N.W. or S.E. The steep dips of the schistosity and the reversal of dip from N.W. to S.E. indicate that the Wissahickon formation at this locality has been subjected to isoclinal folding. It also shows shearing parallel to the axial plane. These relationships have been described elsewhere by the authors (5).

The Granitic Rock

Megascopically, the granite is a medium grained light grey rock. Quartz, white translucent feldspar, and books of white mica from 2 to 4 mm. in diameter are readily recognizable. The mica has no preferred orientation.

The rock occurs sporadically as sheared lenticular masses over an area of a few hundred feet in width, and extends parallel to the strike for about 2 miles from the Schuylkill River to a little beyond the Wissahickon Creek. The long axes of the lenses are horizontal and parallel to the strike of the Wissahickon formation.

MICROSCOPIC DESCRIPTION OF THE HOST ROCKS

Wissahickon Formation

The composition of the biotite quartz schists in the vicinity of the granitic rock may be seen in Table 1. Accessory minerals include garnet, staurolite, tourmaline, zircon, epidote, magnetite, and kyanite.

TABLE 1. MODAL COMPOSITION OF FINE-GRAINED BIOTITE QUARTZ SCHIST

Specimen No.	AD32S	AD48SD
Biotite	10.5	8.0
Muscovite	30.0	16.5
Oligoclase	8.1	5.6
Quartz	43.2	65.5
Accessories	8.2	4.4

In thin sections the schistosity is clearly defined by the parallelism of the micas present. The isoclinal folding is also readily seen in the tight curvature of some of the mica flakes (Fig. 1). The quartz and oligoclase

crystals show a combination of cataclastic texture and sutured boundaries due to various degrees of recrystallization. The garnet and the staurolite have a poikiloblastic texture, the former mineral shows considerable rotation.

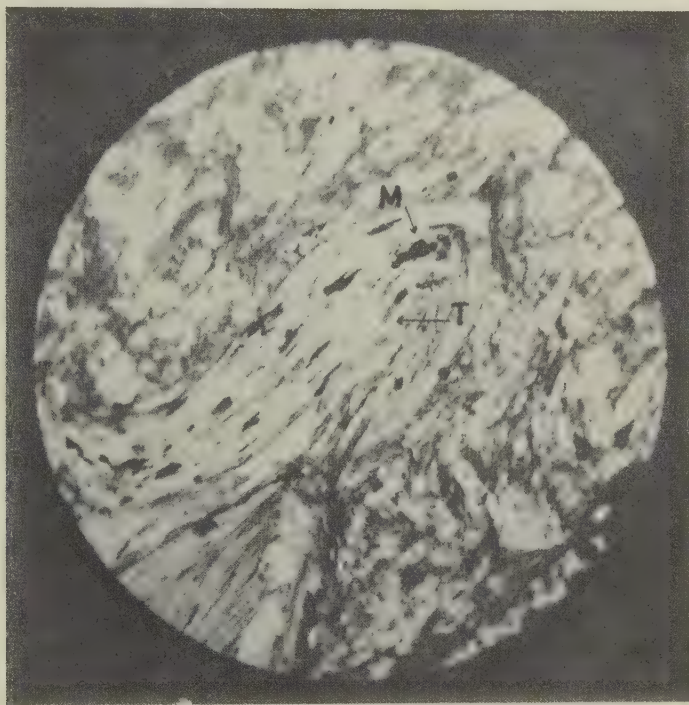


FIG. 1. Thin section of the Wissahickon schist adjacent to the granitic rock. Isoclinal folding of the mica and the distribution of tourmaline and magnetite parallel to the mica cleavage may be seen. T=tourmaline, M=magnetite.

The relationships of the biotite, white mica, tourmaline, and magnetite are of particular interest. The white mica and the biotite are interleaved parallel to the cleavage. It is difficult to interpret the replacement order in such a relationship, but it is assumed that the white mica is replacing the biotite, as it occurs always in greater quantity and is associated with such higher grade minerals as garnet and staurolite. The magnetite and tourmaline occur, often as euhedral crystals, distributed through the micas in parallel alignment to the cleavages (Fig. 1). The tourmaline is strongly pleochroic from colorless or pale mauve to dark blue-green. The indices of refraction of the tourmaline are $\epsilon=1.632$ and

$\omega = 1.658$, which according to Winchell (6, p. 303), would indicate the following composition: dravite 50% and schorlite 50%.

The Granitic Rock

In thin section the granitic rock shows microcline, oligoclase, quartz and white mica. The accessory minerals include, in order of abundance, biotite, magnetite, epidote, and apatite. Both perthites and anti-perthites are present. The proportions of these minerals vary greatly from specimen to specimen, as may be seen in Table 2.

TABLE 2. MODAL COMPOSITION OF THE GRANITIC ROCK

Specimen No.	AD48SA	AD48SG	AD48SJ	AD46S	AD75S	AD-Q2
Microcline	0.00	20.5	26.6	0.0	0.0	26.9
Oligoclase	37.0	36.8	39.0	43.0	54.4	50.0
Quartz	45.0	33.0	15.0	41.5	29.2	14.6
White mica	16.2	6.4	12.3	15.3	15.9	4.7
Accessories	1.8	3.3	7.1	0.2	0.5	3.8
Size in mm.	0.2-2.0	0.2-3.0	0.5-2.0	0.2-2.0	0.1-1.0	1.2-3.0
Size crushed material in mm.	0.01-0.05	0.01-0.05	0.02-0.1	0.02-0.1		0.02-0.1

Under the microscope, the granitic rock shows a texture that is not apparent in the hand specimen. It is a texture that has been produced by a high degree of granulation and recrystallization. In thin section this is shown by sheared channel-ways that pass between large uncrushed mineral grains. The mineral material in the sheared channels is composed of fine grains of quartz and feldspar, which by later recrystallization have tightly sutured contacts. This granulated and recrystallized interlocking texture has been called by Anderson (7) a "pseudocataclastic" texture.

Two important replacement relationships must be noted. The first is the high degree of replacement of microcline by myrmekite. Often the myrmekites grow out from the sheared channels into the microcline. The second important replacement relationship occurs between oligoclase and the white mica, the latter replacing the former. The oligoclase crystals show fringes of white mica that penetrate the crystals. Often the white mica fringes are heavier and better developed when the mica is bordered on one side by a sheared channel-way. Many of the large complete crystals of white mica have the smooth oval shape of the unreplaced oligoclase. The myrmekites too show this type of replacement. The oligoclase of the myrmekite may be replaced by the white mica, leaving the quartz rods undisturbed, and in optical continuity, as they were in the

original myrmekite. Wherever white mica borders quartz, the contact is clearly and sharply defined.

The white mica shows a dual relationship to the biotite; the latter mineral is never present in large percentages as it is in the surrounding schists. In some sections white mica occurs interleaved with the rare biotite, suggesting that it also is replacing that mineral. In other sections the two micas appear to be independent of each other.

ORIGIN OF THE WHITE MICA

The field and microscopic data presented indicate a complex metamorphic background for the genesis of the white mica that is the main subject of this paper. The last stages of metamorphism were hydrothermal and pneumatolytic, as indicated by the tourmaline in the Wissahickon formation and the myrmekitic textures in the granitic rock.

In the schist adjacent to the granitic rock, the white mica appears to replace the biotite. The magnetite and tourmaline are by-products of the replacement reaction. The excess iron released during the reaction was taken up by the magnetite, and some excess iron and magnesium were taken into the tourmaline.

The origin of the white mica in the granitic rock is clearly a late stage hydrothermal reaction. This is supported by the various replacement stages where the white mica replaces oligoclase, both primary oligoclase in the original mineralogy of the granitic rock, and secondary oligoclase in the myrmekites. The hydrothermal origin is also indicated by the frequent occurrence of the white mica adjacent to the sheared channels of the rock. The lack of distortion of the white mica and its replacement of myrmekite also indicate that its origin is post shearing deformation.

J. Berman (2, page 90) speaking of the origin of what he called phenitic muscovite, symplectites, $2V = 35^\circ$, found in the Springfield granodiorite says: the symplectite "occurs only where biotite and plagioclase are in contact, and . . . extends into the plagioclase from the biotite." This interesting relationship is not observed in the granitic rock of the Wissahickon Valley. Occasionally the white mica occurs interleaved with the rare biotite of the granitic rock, as it does in the schist, but usually it occurs with oligoclase without any connection with the biotite. This might suggest a dual origin for secondary white micas having low $2V$ values.

THE WHITE MICA

The mica from the schist and the granitic rock are much alike. Optical data on the mica from both rocks are given in Table 3.

Specimen AD48SA was selected for complete investigation as it was not intimately associated with biotite and five of the 2V measurements

TABLE 3. RANGE OF 2V AND INDICES OF REFRACTION OF MICA FROM THE SCHIST AND GRANITE*

Specimen Number	2V Range		
	Schist		
	2V	β	γ
AD21S	36°–47°	1.599	1.606
AD33SA	24°–48°	1.605	1.612
AD33SB	33°–44°	1.603	1.613
AD47SH	37°–41°	1.600	1.611
AD48SB ^a	39°–40°	1.598	1.607
AD48SD ^b	37°–47°	1.598	1.607
	Granite		
AD23S	28°–49°	1.598	1.605
AD46SB	29°–50°	1.598	1.605
AD47S	41°–46°	1.598	1.606
AD48SA ^c	26°–47°	1.604	1.611
AD48SC	24°–42°	1.602	1.611
AD48SF	25°–43°	1.603	1.610
AD48SI	22°–31°	1.598	1.606
AD48SJ ^d	25°–44°	1.599	1.606
AD74S	40°–47°	1.598	1.605
AD75S	29°–40°	1.604	1.612
AD85S	28°–40°	1.599	1.606

* Indices determined in white light by the immersion method. 2V was determined by six measurements on different mica plates with the U-stage.

^a Schist at contact with the granite dike.

^b Schist inclusion in the granite.

^c Only one grain showed a 2V of 47°, the range in the other five grains was 26°–28°.

^d The AD48S series are from the Wissahickon Creek quarry.

varied from 26° to 28°. Complete indices of refraction for this mica are:

$$\alpha = 1.573, \beta = 1.604, \gamma = 1.611.$$

2V as calculated from the foregoing indices is 48°.44'. This is considerably different from 2V as determined with the U-stage.

Laue photographs were made for specimens AD48SA with the incident beam normal to the cleavage. The resultant photographs show radial streaks or "asterism" (Fig. 2).

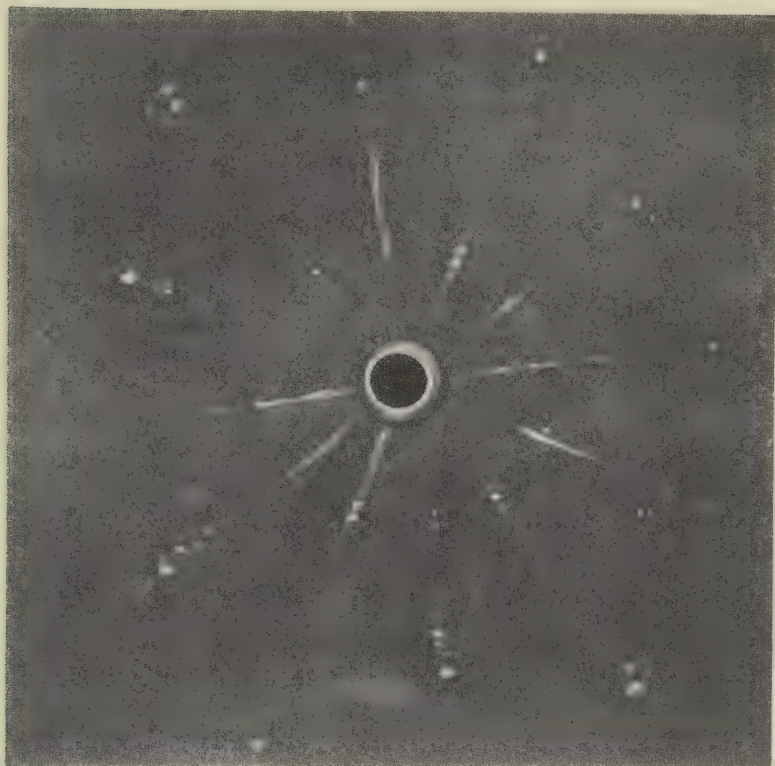


FIG. 2. Laue photograph of the white mica. Incident beam is normal to the cleavage.

Specimen AD48SA was submitted for chemical analysis, the results are shown in Table 4.

TABLE 4. CHEMICAL ANALYSIS OF WHITE MICA
(Analyst F. A. Gonyer)

SiO ₂	46.10
TiO ₂	2.04
Al ₂ O ₃	30.54
Fe ₂ O ₃	3.43
FeO.....	1.96
MnO.....	0.00
MgO.....	1.71
CaO.....	0.07
Na ₂ O.....	3.82
K ₂ O.....	6.54
H ₂ O+.....	3.83
F.....	0.05

100.09

This analysis was recalculated to the formulae of Winchell, Volk, and Hallimond. The results are shown in Table 5.

TABLE 5. PER CENT MOLECULAR COMPOSITION IN TERMS OF THE END MEMBERS OF WINCHELL, VOLK, AND HALLIMOND

End Members	Winchell	Volk	Hallimond
$H_4K_2Al_6Si_6O_{24}$	29.4	55.7	53.5
$H_4K_2(Fe''Mg)Al_4Si_7O_{24}$	53.6		
$H_6K_2(Fe''Mg)_2Al_4Si_6O_{24}$		27.2	
$H_4K_2Fe_2'''Al_4Si_6O_{24}$	17.0	17.1	
$H_4K_2(Fe''Mg)Al_4Si_6O_{22}$			46.5

Per cent of SiO_2 and Al_2O_3 not required or lacking to complete the formulae

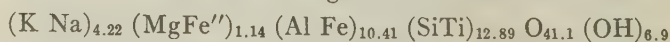
Winchell		Volk		Hallimond	
SiO_2	Al_2O_3	SiO_2	Al_2O_3	SiO_2	Al_2O_3
-3.4	0	+0.8	-3.6	+0.8	0

Table 6 shows the molecular equivalents of the oxides of AD48SA computed on the basis of $SiO_2 + TiO_2 = 600$. This follows Hallimond's method (8, p. 306) as it gives a better means of comparison for minerals that have a constant number of silicon atoms in the molecule. Volk (9, p. 260) also recasts his analyses in this form.

TABLE 6

Al_2O_3	Fe_2O_3	FeO	MgO	$RO + R_2O_3$	RO	H_2O
226	16	20	36	298	98	162

The end members of Winchell, Volk, and Hallimond are convenient symbols for expressing the composition of the muscovite system. They do not, however, give a true expression of the content of the individual unit cell. Therefore, the chemical analysis was also recast in terms of the structural formula suggested by H. Berman (10) in his recent reclassification of the silicates. The following formula is the result:



In terms of total $(Mg, Fe''', Fe'', Al'') + (Si, Al)$, this represents a variation of +1.9% from the theoretical formula as advanced by H. Berman.

INTERPRETATION

The low values obtained from 2V on the white mica of the granitic rock originally suggested that the mica was a phengite. This opinion was based on Winchell's diagram (6), on Volk's (9) revision of the muscovite group, and on the work of J. Berman (2).

Consideration of the indices of refraction of the white mica, Table 3, indicates two groupings, one with gamma about 1.611 and the other with gamma about 1.605. The ranges of 2V however seem to be independent of these two groups. According to Winchell's data on the muscovite system (6, p. 268) the beta indices are in the Mg-phengite range ($1.59 \pm$) and the Fe''-phengite range ($1.61 \pm$). In terms of Volk's (9, p. 263) recent work the high beta values also indicate an increasing amount of the Fe''' muscovite molecule. When the indices of refraction of AD48SA are adjusted to the iron content diagram of Kunitz (11, p. 380), an iron content of about 4% is indicated. This checks closely with the total iron (Fe'' + Fe''') content as computed from the chemical analysis.

It is impossible however to get an adjustment on Winchell's composition diagram for the muscovite system, as the 2V value of the white mica, specimen AD48SA, is too low. Extrapolation would indicate a phengite content of near 90%. Volk's diagram on the relation of 2V to phengite content (9, p. 264) would also have to be extended to include the low 2V value of the white mica.

Perusal of the literature would indicate that no correlation can be established between indices of refraction and low 2V values.

Other factors were therefore investigated to explain the optical properties observed.

The work of Hendricks (12) on the structures of layered minerals and particularly the work of Hendricks and Jefferson (13) on the micas was taken as pertinent to the problem. Hendricks and Jefferson (13, p. 768) have stated that diffuse scattering of x-ray indicates random shift of the layers involved in the mica structure. A Laue photograph of the white mica shows "asterism" which Hendricks and Jefferson say is equivalent to the continuous Weissenberg curves which result from random shift (13, p. 767-768). It is thus indicated that the white mica has a structure involving random shift of the layers. It is interesting however to note that Hendricks and Jefferson state that this condition is not observed in muscovite (13, p. 767). Certainly there is a marked dissimilarity between the Laue photograph of muscovite given by Hendricks and Jefferson (13, p. 769) and by Jackson and West (14, p. 216) and the photograph of AD48SA. This type of behavior is characteristic of biotite, and the other micas.

Consideration of the foregoing would imply perhaps that the white mica was not a true muscovite. It might be suggested that the structure is an attribute of the replacement origin of the white mica. The degree of randomness of the structure would then perhaps be related to the degree of replacement. If random shift influences the optical properties this may explain the fact that 2V of the white mica is highly variable, as it would be influenced by the degree of random shift and the degree of replacement.

The questions raised by the foregoing optical and x-ray data make necessary a consideration of the chemical composition of the white mica.

It is known that as the phengite molecule increases in the muscovite system the value of 2V decreases. The magnesia content of the white mica, AD48SA, is not unusually high, though it may be considered moderately high. Some of the recent analyses published by Volk (9, p. 259) show much higher magnesia content, but these high magnesia muscovites have 2V values considerably higher than the mica being considered here. It would seem, therefore, that magnesia alone is not responsible for the abnormally low values of 2V previously given. Volk (9, p. 264) points out however that considerable amounts of ferric iron in combination with small amounts of phengite will cause a decrease in the value of 2V. An examination of the chemical analysis of AD48SA shows a high ferric iron content in combination with the magnesia. This then may explain the very low 2V value of the specimen, lower than values given by either Winchell or Volk, it does not however account for the variable nature of 2V.

It should be pointed out, however, that ferric iron alone without magnesia will reduce the size of 2V. The lowest 2V (with one exception to be noted later) for the muscovites reported on by Jakob (15, p. 445-446) is $36^{\circ} 10'$, the Fe_2O_3 content for this specimen, #14, is 3.85%, the MgO is only 0.74%.

Of particular interest is the unusually high soda content of the white mica, AD48SA. The ratio of soda to potash is approximately one to two. Published analyses (16 and 17 and bibliography) show that the usual soda-potash ratio for muscovite ranges from one to five to one to ten. The analyses published by Winchell (18, p. 421) include two that have similar soda-potash ratios. Out of 75 analyses published by Boeke (19 p. 86) only four have a soda-potash ratio of 1:2, and of these analyses only one has a soda content between 3 and 3.5%, none are over 3.5% (p. 116). On the other hand the soda-potash ratio is not sufficient to call the mica paragonite. Three analyses of paragonite recently published by Stevens and Schaller (20, p. 526) show for that mineral soda-potash ratios of from 3:1 to 7:1. The influence of this low soda-potash ratio on

optical properties is at present indeterminate. However, it is not probably great, as the lowest 2V for a muscovite reported by Jakob (15, p. 455-446, #18) is $29^{\circ} 20'$, the soda-potash ratio is 1:6. The high soda content of the white mica is probably due to its origin, the soda coming from the replaced oligoclase.

SUMMARY AND CONCLUSION

The white mica, AD48SA, has been described from as many view points as possible in the hope of giving a complete picture of all factors involved. The tectonic and paragenetic history of the host rock is complex which perhaps accounts in part for the peculiar properties of the mica.

A search of the literature has revealed no white mica with equivalent chemical and optical characteristics. The optics of the mica are abnormal in that the indices of refraction are fairly constant while the value of 2V shows wide variation. Chemically, it is interesting to note the unusually high soda content of the mica in combination with moderate magnesia and high ferric iron. The idea is advanced that random shift in the structural planes of the mica may have some bearing on the low and variable values of 2V. It also seems that Volk's statement that moderate amounts of magnesia in combination with ferric iron will decrease the value of 2V is correct. It is however impossible to say which of these factors, or combination of factors, is responsible for the effects observed.

In conclusion the following points may be made:

1. It is not always possible to get a good approximate chemical composition of a white mica from the present optical diagrams.
2. It is not advisable to deduce high phengite content of a muscovite in terms of 2V alone.
3. It is not always advisable to deduce high ferric iron in combination with moderate magnesia content from 2V alone.
4. None of the existent diagrams show the influence of ferric iron in decreasing 2V.
5. In view of the first three points it would seem that the only accurate way to determine the composition of a doubtful muscovite is by a chemical analysis.
6. It may be of value if future studies in the muscovite system take the genetic factor into consideration.
7. Low values for 2V in a white mica may be caused by five factors acting singly or in combination: high magnesia content, high ferric iron content, moderate magnesia and high ferric iron content, random shift in the lattice structure, and a hydrothermal replacement origin.

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THE STRUCTURE OF STILPNOMELANE REEXAMINED

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ABSTRACT

New x-ray data show the distribution of ions normal to the basal cleavage in the layer silicate stilpnomelane. Since it is similar to talc and biotite a structure consistent with its properties can be proposed. It explains satisfactorily the behavior of the mineral including its base exchange of K for Tl. Stilpnomelane is an important essential constituent of certain iron formations.

INTRODUCTION

The writer (1) made an attempt in 1937 to determine the composition and crystal structure of stilpnomelane. At that time the mineral had been reported from the quartz veins in iron formations and from the chlorite-epidote-albite schists in New Zealand (8 and 11). Recently it has been identified in large amounts in the iron formations of the Cuyuna and Mesabi ranges of Minnesota. There it is one of the three principal iron silicates, iron talc, to be described in detail shortly, being the second and greenalite the third.

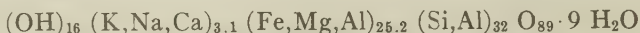
As was pointed out previously, (1, p. 912) stilpnomelane may readily be mistaken for biotite under the microscope. Like biotite it is negative with a small optic angle and has similar pleochroism. In the hand specimen it resembles either biotite or chlorite, but is much more brittle. Its cleavage is excellent. Basal sections with partially developed hexagonal outlines have been observed. These properties and the discussion that follows make it certain that stilpnomelane has a layer structure and is related to the micas and chlorites.

CHEMICAL COMPOSITION

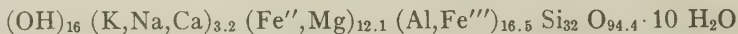
Nothing essentially new can be added with regard to the chemical composition of stilpnomelane. As a constituent of the iron formations it is so fine-grained and intergrown with other minerals that it cannot be separated for analysis. But there is no reason to believe that it differs materially from published analyses (1), to which the reader is referred. Table 1 is copied partly from the original paper, but with some additions calculated from new analyses by Hutton (11). The number of positive ions in the table have been recalculated from the chemical analyses on the basis of 32 Si ions per unit cell. This represents the largest number of Si ions possible in a talc-like layer structure in which all tetrahedral positions are occupied by Si, and leads to an average comparative formula: $\text{OH}_{16} (\text{K}, \text{Na}, \text{Ca})_2 (\text{Fe}, \text{Mg}, \text{Al})_{29} \text{Si}_{32} \text{O}_{93} \cdot 13 \text{H}_2\text{O}$.

The positive charges necessary to satisfy the O and OH charges are also shown in Table 1. It is quite evident that they are greatly in excess of those needed for a talc structure containing 32 Si, which would be 80 O and 16 (OH) = 176 negative charges. Also, the number of cation positions in such a talc structure does not exceed 24 while the actual numbers in the table range from 30.0 to 32.

Based on the size of the unit cell assumed at that time and the specific gravity, it was calculated in the original paper (1, p. 915) that the total content of the unit cell could be reduced to the following formula for No. 4 of Table 1:



It has been found since, as will be shown below, that the unit cell is actually about 6% larger and that for sample No. 4 of Table 1, its formula is very close to:



Since the highest total number of cations is 64, one may conclude with some assurance that this is the maximum number of positions available in the structure. In some stilpnomelanes with relatively low specific gravities the 32 Si positions may not be all occupied by Si, but also by Al, as was assumed in the earlier paper. In No. 5, for example, 31 positions would be occupied by Si instead of 32, provided the observed specific gravity and theoretical density are correct. At no time would it be possible, however, to have just simple mica or talc layers without additional structure elements in the cell as Hutton (11, p. 191) apparently tried to assume. Besides leading to disagreements of intensities of reflections, the density of such a structure would scarcely reach 2.50. For No. 8 in Table 1 it would be 2.4, for example. The condition of H₂O in the structure is only partially explained by the dehydration curves shown in the papers by Gruner (1) and Hutton (11, p. 190). It is certain that part of the water is present as (OH) ions. Hutton shows that at least 3% of the H₂O of No. 9 in Table 1 can be removed over concentrated H₂SO₄. This water is entirely regained upon exposure to the atmosphere for eight hours. The channels in the structure described below plausibly explain this behavior.

X-RAY DATA

Stilpnomelanes Nos. 3 and 4 gave excellent powder photographs with iron radiation and precision cameras of 57.3 mm. radius. These have already been published (1, p. 919). Films of samples Nos. 6 and 7, while still distinct, were poorer in quality. Even in the hand specimens they appeared somewhat altered as indicated by their brownish colors. X-ray photographs obtained from the microscopically fine-grained stilpnome-

TABLE 1. NUMBER OF IONS IN A UNIT VOLUME CONTAINING 32 Si IONS

	1	2	3	4	5	6	7	8	9
Si	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
Al	3.4	4.4	4.0	5.3	5.5	4.1	5.2	5.6	6.2
Fe'''	7.3	8.8	6.3	11.2	12.3	2.9	12.6	13.5	11.3
Fe''	15.2	9.0	12.2	7.7	9.6	14.2	3.5	2.0	8.4
Mg	2.2	6.3	6.2	4.3	1.5	9.0	9.9	8.1	3.0
Mn	0.0	0.7	0.2	0.1	0.3	0.5	0.0	0.4	0.0
Ca	0.3	0.0	0.7	0.1	0.4	0.0	0.0	1.5	0.4
Na	1.0	1.2	0.4	0.1	0.0	?	0.0	0.0	0.0
K	2.0	1.6	1.9	3.0	0.4	?	0.0	1.5	1.9
H+	32.0	34.0	28.0	26.9	31.0	53.1	43.0	31.7	30.8
H-	9.5	8.7	8.7	9.3	12.6	10.7		3.6	6.5
Al+Fe'''	10.7	13.2	10.3	16.5	17.9	7.0	17.8	19.1	17.5
Al+Fe+Mg+Mn	28.1	29.2	28.9	28.6	29.2	30.7	31.2	29.6	28.9
Σ cations without H and Si	31.4	32.0	31.9	31.8	30.0	30.7	31.2	31.8	31.2
Σ +charges without H	195	202	200	205	206	196	208	211	206
Mol. Weight	4374	4300	4243	4294	4410	4356	4235	4250	4313
Sp. Gr.	2.82		2.82	2.88	2.85			2.78	2.84
Theor. Density	2.94	2.89	2.85	2.89	2.96	2.93	2.85	2.85	2.90

1. Theodor Mine. Described by Holzner (2).

2. Mont Chemin. Described by Jakob (7).

3. Genoa Mine of the Mesabi range. Described by Grout and Thiel (6). This material contained a little quartz. The original analysis was recalculated on the assumption that 3% of the reported SiO₂ was present as quartz.

4. Baern (Sternberg-Bennisch), Moravia. Described by Gruner (1).

5. North Wales. Described by Hallimond (5).

6. Westfield, Mass. Average of two analyses. Described by Shannon (3).

7. Lambertville, N. J. Described by Shannon (4) as chalcodite.

8. Otago, New Zealand. Described by Hutton (11).

9. Zuckmantel, Silesia. Described by Hutton (11).

lane in the iron formations mentioned were of fair quality. No x-ray photographs were available of stilpnomelanes Nos. 1, 2, 5, 8, and 9. Fankuchen (11, p. 201) has made oscillation photographs of portions of stilpnomelane crystals which are rather complicated. Based on very weak reflections he concludes that the mineral has a superlattice of about the following dimensions: $a_0 = 22.0 \text{ \AA}$, $b_0 = 38.0 \text{ \AA}$, $c_0 = 36.2 - 37.9 \text{ \AA}$. In other words, his unit cell would be about 48 times the author's and would contain over 2000 ions. Apparently this is a similar case to that de-

scribed for the micas by Hendricks (12, p. 770). Fankuchen's observations do not conflict essentially with the present ones. He does not advance a structure scheme of his own. What astonishes the writer are the considerable fluctuations in the lengths of the c axes, as given by Fankuchen. In the present investigation the thicknesses of the layers varied from 12.07 to 12.18 Å. His range apparently from 12.07 to 12.63 Å, differences much greater in proportion than any encountered so far in any layer silicates, not excluding the chlorites. Fankuchen lists no x -ray powder photographs. In those of the writer's not more than four basal reflections could be indexed with certainty. More recently the writer has obtained rotation photographs from small flakes of Nos. 3 and 4 and was able to measure basal reflections including the 11th order. Their intensities are listed in Table 2. Also, by selecting thicker basal sections and trimming them to about 1 mm. diameter, measured in the plane of the base, it was possible to obtain and index reflections of planes 060, 200, and 400. Based on these new data the volume of the smallest unit cell was increased from 578 Å³ to 614 Å³.

TABLE 2. THEORETICAL AND OBSERVED INTENSITIES OF BASAL REFLECTIONS OF STILPNOMELANE. FE RADIATION

Indices	001	002	003	004	005	006	007	008	009	0010	0011
Theoret. I	200	0.3	12	16	0	0.2	0.05	2.0	0.6	0.8	0.5
Observed I Powder Sample 7	10+	0	3	3	0	0	0	1	0.5	0	0
Observed I Powder Sample 4	10+	faint	5	5	0	0	0	2	0.5	0.5	?
Observed I Rotation Sample 4	very strong	1	15	15	0	0	doubt- ful	2-3	0.5	1	faint

The dimensions for No. 4 are: 001 = 12.12 Å, b_0 = 9.40 Å, 100 = 5.39 Å. The dimensions for 100 and b_0 are similar to those of cronstedtite (9) and other layer silicates high in iron. This gives us a workable unit cell as compared with Fankuchen's, though slight changes may be necessary in it at some future date.

The theoretical intensities of the basal reflections were calculated as follows:

The bulk of the ions is distributed as in the individual talc layers. As-

suming monoclinic symmetry a plane of symmetry lies in the plane of the a and c axes. Atoms in this plane are shown in Fig. 1. Their positions with respect to a basal plane of reference are given in the figure. The distribu-

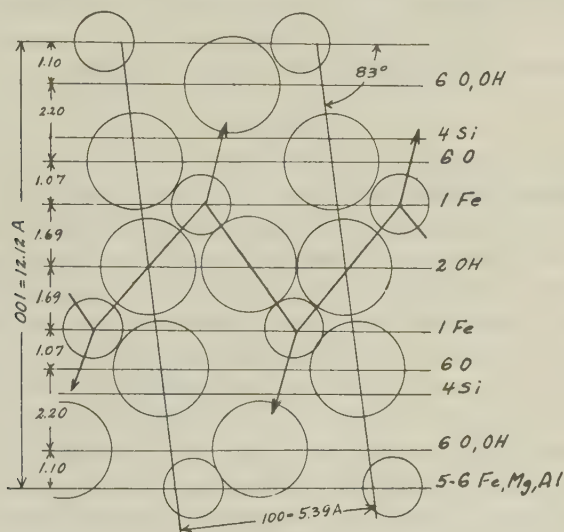


FIG. 1. Distribution of ions in the plane of symmetry. All positions shown are in this plane. Small circles are Fe, Al, or Mg.

tion of the atoms in the plane half way between the talc layers is shown in Fig. 2. In computing the structure factor it was assumed that Fe, Mg, and Al are distributed statistically over the available positions. The mean

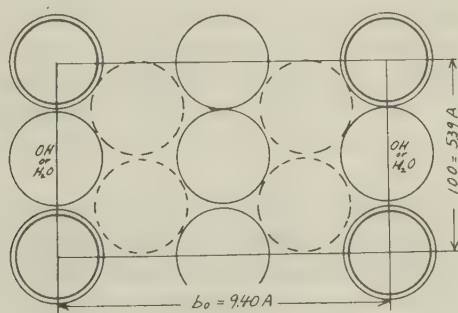


FIG. 2. Distribution of atoms in a plane halfway between talc layers. OH and O ions full rings. K ions double rings. H_2O broken line rings.

of the scattering power of each of these positions was taken to be the same and calculated from the chemical compositions. There is no doubt that this method introduces considerable errors to which must be attributed

some of the disagreements in Table 2. For example, if two Mg ions filled the two cation positions between the talc layers leaving more Fe'' ions for the octahedral positions, theoretical and observed intensities would be in very good agreement. It was not possible to determine how much more intense the reflection 001 is than 003, but it is certain that it is several times as great, and possibly as much as 15 to 20 times.

STRUCTURE

The significant feature of the structure is that 12.12 Å is the simplest *x*-ray period, with indices 001. There is not the slightest indication in the films that the indices of the basal reflections given in Table 2 need to be doubled and that other basal reflections might occur between them. This means that the structure must be simpler than a combination of any known layers. The periods of such combinations would be multiples of 12.12 Å, and would all have several reflections at such distances as 24/3, 24/5, 24/7, 24/9 Å, etc. They were discussed before (1, p. 918). There are, however, other possibilities for interpreting the chemical composition of the mineral. For example: (a) Instead of having one octahedral gibbsite layer between two tetrahedral layers, two such layers could occur between tetrahedral layers. The thickness of a layer would be about 11.5 Å. The formula would be about $(\text{OH})_4\text{M}_8(\text{SiAl})_8\text{O}_{26}$. If K or H₂O were between the layers the thickness would be about 12.2 Å. (b) The serpentine structure proposed by Bragg which is 14.6 Å in thickness can be simplified with the result that it would be only 12.2 Å thick and have a layer structure. (c) A layer consisting entirely of two tetrahedral SiO₄ layers facing each other, 7.2 Å thick, combined with a nearly neutral gibbsite layer 4.9 Å in thickness. Its formula would be $(\text{OH})_{12}\text{M}_{4-6}(\text{SiAl})_4\text{O}_{16}$. Theoretically, there seems to be no objection to such a combination.

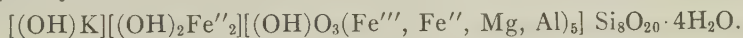
All these possibilities were thoroughly tested but had to be rejected. The only structure that will fit the observed intensities is similar to the one proposed earlier (1), but it is now possible to fix the ions with considerable assurance.

It is fundamentally a talc structure. There is just sufficient room between the layers for (OH) or O ions to slip in between the nearest oxygens of the talc. The layers are stacked in such a manner that the hexagonal rings more or less fit on each other as in micas. There are 2 (OH) ions halfway between two unit layers or, what is more probable, one O ion and one (OH). They probably lie at the intersections of alternate planes of symmetry and theoretical cleavage planes, that is, parallel to the *a* axis. Two cations of Fe'', Mg, or Ca are held by the O and (OH) ions as indicated in Fig. 1.* Some of the valences of the cations are bound by the

* There are also other O ions in contact with the Fe''.

(OH) positions of the octahedral layers. The (OH) in these positions are replaced in part by O which also explains why so many trivalent ions are found in the octahedral positions of the talc layers. The ferrous ions outside of these layers would obey Pauling's rule by having three bonds of 1, $\frac{1}{2}$ and $\frac{1}{2}$ valences. It would be chiefly by these $\frac{1}{2}$ valence bonds to the octahedral layers that the structure would be held together. It is quite possible that these bonds might have a strength of one depending upon the numbers and kinds of cations in the octahedral layers. In that case all of the O positions between the layers would be filled by (OH).

The K ions fit easily into the rows of large spaces left between the chains of (OH) and Fe, (Fig. 2). They lie in the theoretical cleavage planes. Their charges are probably partially satisfied by the O ions in the octahedral OH positions. There is, however, a distinct possibility that (OH) ions are in the positions indicated. There are 5 positions available for H₂O unless one of them is filled by OH as just mentioned. The smallest completely filled unit cell would then contain:



The brackets indicate the ions which belong together structurally. This formula has 50 negative charges which is in good agreement with the + charges of Table 1. By converting the only remaining (OH) in the octahedral layer to O a maximum of 51 charges may be reached.

DISCUSSION

The proposed structure must be able to explain the peculiar properties of the mineral. The mineral is remarkably stable, being found in schists and slates. The thickness of the layers is very uniform regardless of changes in composition. The uniformity of the radii of O and (OH) between the talc layers accounts for both of these properties and for the fact that no breakdown occurs below 550° C. in an atmosphere of CO₂ as does in nontronite (10) and vermiculite.

As was pointed out previously (1, p. 922) thallium readily replaces K. The arrangement of the K ions in wide channels in the structure easily explains this rapid substitution. Boiling in HCl or H₂SO₄ produces identical sheets of amorphous silica so well known in similar experiments with biotites. This also suggests their similarity. Experiments in which talc-like structures were produced in bombs are also significant as already discussed (1, p. 923).

While the amount of Al in the structure is not large, no reliable stilpnomelane analyses have been reported without several per cent of Al₂O₃. As a matter of fact, most of the Al₂O₃ found in the iron formations of the Cuyuna and Mesabi ranges seems to be in the mineral stilpnomelane

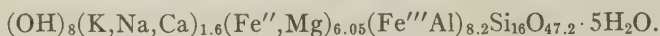
as discovered recently. Also Mg is never absent. The writer believes that these two elements are essential to the formation and particularly to the stability of this otherwise unusual structure. It is, of course, probable that small amounts of the Al ions substitute for Si. Chemical analyses suggest that not all available positions are necessarily filled in the structure, a property characteristic of many layer silicates. The spaces available for OH and H₂O are slightly more than sufficient to accommodate them. The dehydration curves of stilpnomelane (1, p. 916) are in excellent agreement with the distribution of OH and H₂O.

CONCLUSIONS

Based on the new data it is found that the unit cell of stilpnomelane is about 6% greater than published previously.

$$001 = 12.12 \text{ \AA}, b_0 = 9.40 \text{ \AA}, 100 = 9.39 \text{ \AA}.$$

New basal reflection calculations lead to an unusual type of layer structure related to biotite and iron talc (a mineral to be described shortly). The formula for the stilpnomelane (No. 4) for which the most complete data are at hand is for two smallest unit cells:



Simplified to a structural formula of one cell it is:



The structure contains channels parallel to the *a* axis in which K ions may be situated. These may be replaced by thallium and probably other ions of suitable dimensions or H₂O. Between the channels are chains of Fe-OH-Fe-O ions which hold the main layers apart. Mg and Al are thought to be essential to the structure. Without them probably quartz and magnetite would have resulted. This is the impression one receives in studying the iron formations of the Mesabi and Cuyuna ranges in which stilpnomelane occurs in very large amounts as an essential constituent.

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OCCURRENCE OF GABBRO-WEHLRITE NEAR LOCHALSH, ONTARIO

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ABSTRACT

Gabbro-wehrlite consisting of more than 80% dark constituents, but in excess of 10% plagioclase, forms the marginal facies of a mela-olivine gabbro intrusion near Lochalsh, about 150 miles north of Sault Ste. Marie, Ontario. This exceptionally fresh rock is of interest as a link between the gabbro and peridotite clans.

In his report on the iron deposits of the Missinaibi map area, E. Thompson¹ mentioned the occurrence of peridotite at the northwest end of Dog Lake, about $1\frac{1}{2}$ miles southeast of the Canadian Pacific Railway station Lochalsh. The intrusive body is roughly elliptical in outline, with its major axis striking almost due east. It is slightly over one mile long and up to 1,500 ft. wide, forming a prominent ridge rising more than 300 ft. above the level of Dog Lake. Thompson described this remarkably fresh basic rock as consisting essentially of pyroxene and olivine, with lesser quantities of plagioclase and biotite, and some serpentine and hornblende as secondary products.

The present writer investigated the occurrence referred to by Thompson, in connection with a search for war-important minerals. Microscopic examination of a considerable number of samples taken at various points of the intrusion revealed that its plagioclase content exceeds the amount of leucocratic constituents allowed by most petrographers in rocks classed as peridotites. Actually the mass consists of a core bearing from 20 to 45% plagioclase, and a more melanocratic border zone averaging less than 20% plagioclase. In no instance was the feldspar content less than 10% of the total constituents.

According to the amount of feldspar present, the intrusive ranges in composition from a mela-olivine gabbro (3312 P) to a rock approaching wehrlite. Following Johannsen's classification,² the marginal facies may be termed gabbro-wehrlite (3'312) as a rock containing in excess of 80% but less than 95% dark constituents. With an average content of more than 60% olivine, the border zone represents a rather unusual rock linking the gabbro and peridotite clans.

The marginal facies has a mean width of approximately 300 ft. and attains about 700 ft. at the east and west ends of the intrusive body, respectively. The change from the mela-gabbro core to the gabbro-wehrlite

¹ Collins, W. H., Quirke, T. T., and Thompson, Ellis, Michipicoten iron ranges: *Can. Geol. Surv., Mem.* **147**, 152 (1926).

² Johannsen, A., *A Descriptive Petrography of the Igneous Rocks*, I, insert slip, p. 145 (1931).

border is gradational though in places the transition appears in less than 50 ft.

Megascopically, the gabbro-wehrlite is a massive, dark-green to dark-

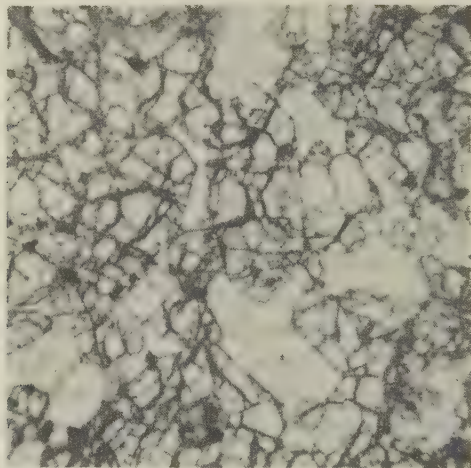


FIG. 1. Thin section of gabbro-lherzolite showing olivine (gray, high relief), bytownite (light-gray, low relief), and iron ore (black). $\times 22$. One Nicol.

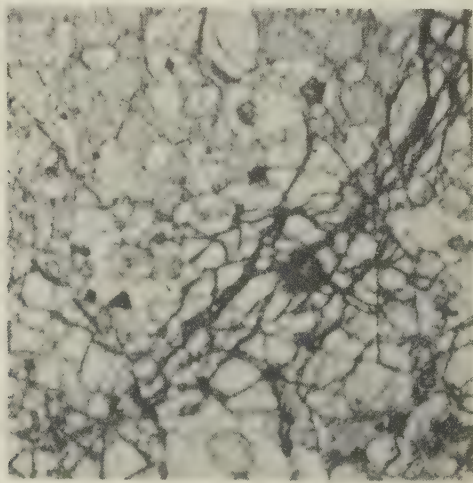


FIG. 2. Thin section of gabbro-lherzolite showing olivine (medium-gray, high relief), augite (dark-gray, distinct cleavage), bytownite (light-gray, low relief) and iron ore (black). $\times 23$. One Nicol.

gray rock. More exposed surfaces generally are somewhat lighter in color, owing to a bleaching of the feldspar. In contrast to the rather coarse appearance of the mela-gabbro, the gabbro-wehrlite gives the impression of a fine-grained rock although reflected light discloses scattered poikilitic cleavage surfaces of pyroxene up to $\frac{3}{4}$ centimeter long.

The microscopic texture of the gabbro-wehrlite is characterized by a hypautomorphic pattern of plagioclase and pyroxene several millimeters in diameter, which contain abundant poikilitic inclusions of olivine.

The fine-grained appearance of the rock in the hand specimen is accounted for by the fact that quantitatively speaking the olivine inclusions exceed the host minerals plagioclase and pyroxene. Occasionally the pyroxene encloses not only olivine but also more or less corroded small laths of plagioclase. Apatite, magnetite and chromite form automorphic crystals of microscopic size, the ores occurring mainly in the olivine.

At places there are indications of what might be called a banded texture. Individual bands are generally quite irregular and extend only short distances. They appear to be a primary feature and owe their origin to a process by which the light or dark components were slightly concentrated. This texture is prominent in the mela-gabbro facies (Fig. 3). Light colored irregular masses up to 3 ft. in diameter resembling fragments were observed in the center of the intrusion. Here and there dikes consisting of essential bytownite and accessory diallage were seen traversing both the gabbro-wehrlite and mela-gabbro. According to microscopic evidence, these dikes were formed after the consolidation of the two main facies.

Under the microscope, the primary constituents of the gabbro-wehrlite are olivine, bytownite, augite, biotite, pigeonite, chromite, magnetite, and apatite, named in the order of their abundance. Secondary minerals include serpentine, talc, chlorite, hornblende, iddingsite, carbonate and magnetite. The alteration products rarely exceed 10% of the total components, and in some thin sections are less than 1%.

The constituents of the gabbro-wehrlite are essentially the same as those observed in the mela-gabbro facies, the difference in the composition of the two rocks being due to the smaller plagioclase content in the outer portion of the intrusion.

Under the microscope, olivine, the most abundant constituent, appears as more or less well developed crystals representing doubly terminated prisms (Fig. 1). Their size varies from 0.1 to 3.0 millimeters, the average being approximately 0.4 millimeter. Many individuals show signs of magmatic corrosion, particularly those enclosed in pyroxene. The mineral is clear and colorless in transmitted light. In general there is extraordi-

narly little alteration of the olivine except on more exposed surfaces, but even here the development of serpentine has only infrequently advanced beyond the initial stage.

The plagioclase is a colorless bytownite close to Ab_1An_3 in composition. It occurs as polysynthetic twins after the albite law. Pericline twinning is not uncommon, but combinations of albite and Carlsbad twins are rare. Individuals average about 2 millimeters in diameter and attain

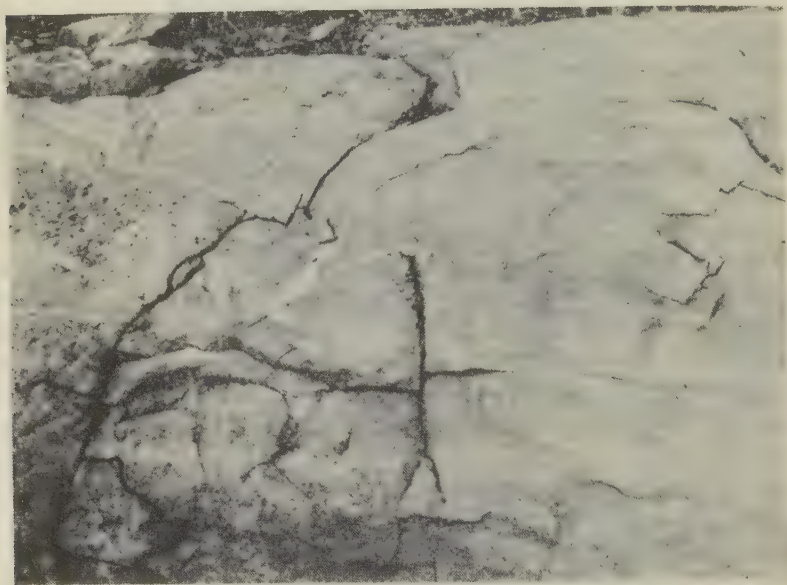


FIG. 3. Banded texture of mela-gabbro facies. Note late labradorite dikelets (white). Horizontal width of picture about 7 ft.

a maximum size of 5 millimeters. In most thin sections, the plagioclase is traversed by numerous cracks radiating from the olivine inclusions, even where the latter appear to be quite fresh.

The microscope reveals the presence of two clinopyroxenes. Predominating is augite which forms xenomorphic individuals up to $\frac{3}{4}$ centimeter long. It shows distinct pleochroism in brownish shades, rather strong birefringence, positive optical character, $2V = \text{ca. } 65^\circ$, and $Z \wedge c = 48^\circ$.

In some thin sections, the augite is accompanied by small amounts of pigeonite. Its optical properties include weak pleochroism, moderate to low birefringence, positive optical character, $2V = \text{ca. } 50^\circ$, and $Z \wedge c = 40^\circ$. The mineral shows a tendency to be automorphic.

At places the pyroxenes have been altered to a greenish hornblende. The secondary nature of the hornblende is attested to by the fact that it penetrates the pyroxene in fibers.

Strongly pleochroic, reddish-brown biotite occurs as an accessory in the form of irregular flakes intergrown with the other dark constituents. Some flakes attain a size of 3 millimeters, being visible in the hand specimen. In slides of weathered gabbro-wehrlite, biotite may be observed along cleavage planes in pyroxene and in cracks traversing olivine. This secondary biotite is commonly associated with irregular aggregates of secondary magnetite.

Chromite and magnetite occur in sharp, small crystals in olivine and, to a minor extent, in the other constituents. Some secondary magnetite was observed in partially decomposed olivine and pyroxene. It forms small irregular aggregates intimately associated with the other decomposition products.

Though persistent the chromite content rarely exceeds 1%. It is interesting to note that on the average the gabbro-wehrlite border zone carries more chromite than the mela-gabbro core. According to the observations of the writer, however, there are no indications of chromite concentrations in the portions of the intrusion that are accessible to examination.

Apatite is present in exceedingly small quantities. It forms minute, more or less corroded prisms.

The order of crystallization of the primary constituents of the gabbro-wehrlite is ores, apatite, olivine, pigeonite, plagioclase, augite, biotite.

Specimens from different points of the border zone show certain variations in the proportions of the primary minerals of the gabbro-wehrlite. Rosiwal counts gave the following range expressed in volume percentages: olivine 55 to 75%, bytownite 11 to 21%, pyroxene 6 to 22%, biotite 0 to 2%, ores 0.7 to 3.2%. The following average figures were obtained from 18 thin sections: olivine 61%, bytownite 18.5%, pyroxene 12.4%, biotite 1.6%, ores 1.8%, serpentine and other secondary products 5.1%.

The age relations of the intrusive body consisting of gabbro-wehrlite and mela-olivine-gabbro to the surrounding rock formations are somewhat obscured by the fact that its periphery is largely buried under talus slopes and glacial debris. The older rocks are essentially Keewatin volcanics which in places are invaded by minor masses of pink granite. At one point, tongues of the latter were seen to be cut off by the basic intrusion.

Several dikes of fresh quartz diabase striking in a northwesterly direction can be traced close to the gabbro-wehrlite border. Their older age

CHEMICAL ANALYSIS OF GABBRO-WEHLRITE FROM NW-FLANK OF
"PERIDOTITE HILL" NEAR LOCHALSH

SiO ₂	41.38
Al ₂ O ₃	6.00
Fe ₂ O ₃	2.16
FeO	10.23
MgO	31.89
CaO	4.13
Na ₂ O	.76
K ₂ O	.08
H ₂ O+	2.19
H ₂ O—	.10
CO ₂	.40
TiO ₂	.28
P ₂ O ₅	.04
Cr ₂ O ₃	.40
MnO	.18
	<hr/>
	100.22

Spec. Grav. 3.144

Analysts R. B. Ellestad and B. Smith, Minneapolis

may be inferred from the fact that no quartz diabase dikes are observed traversing the basic mass.

At the west end of the prominent ridge composed of olivine rich rock, the gabbro-wehrlite border zone is cut by a dike of coarse olivine gabbro about 40 ft. wide. Striking approximately northwest this dike resembles lithologically the late olivine diabase intrusions found in the region east of Lake Superior.

The foregoing evidence places the age of the ultra-basic body between the intrusion of the quartz diabase and olivine diabase dikes. Both are generally regarded as Keweenawan. The mineralogical composition and extraordinary freshness point toward a possible affiliation with the olivine diabase intrusions.

ACKNOWLEDGMENTS

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MINERALOGY OF THE LITTLE LONG LAC GOLD AREA, ONTARIO

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ABSTRACT

The mineralogy of the Little Long Lac deposits, like that of many other gold deposits of northern Ontario, is relatively simple. In the present study nine sulphides, two tellurides, two sulpho-salts, and six other metallics, including gold, have been identified in hand specimens and polished sections. In addition three supergene minerals have been observed in specimens from one mine. The latter are of interest as representing the occurrence of a shallow zone of secondary enrichment within the Canadian Shield.

INTRODUCTION

In a paper which has recently appeared (Armstrong, 1943) there are presented outlines of the general geological relationships, and discussions of the mineral paragenesis for each of seven gold mines in the Little Long Lac area. The present paper is submitted in order to supplement, in detail, the information now available concerning the mineralogy of the area.

Dr. E. L. Bruce in his several reports and papers (1935, 1936, 1939), and W. Samuel (1937), have discussed the mineralogy in general terms. A. W. Johnston (1935) and H. F. Morrow (1940) have likewise devoted some attention to the mineralogy incidental to their broader discussions of the Bankfield and MacLeod-Cockshutt mines, respectively. Professor Ellis Thomson's paper (1935) on the mineralization of the region provides important information concerning the mineralogy of the earlier prospects and developments. Further valuable data, particularly concerning the size of the mineral grains, are to be found in various reports of the Bureau of Mines, Ottawa (1935, 1936, 1937, 1939).

The information presented below has been obtained from the study of numerous hand specimens and polished sections representative of the ores from the various mines. This work was carried out at the University of Chicago in the laboratories of the Department of Geology and Paleontology, to the Chairman of which, Dr. E. S. Bastin, the writer is deeply indebted for research facilities and kindly encouragement.

MINERALOGY

The mineralogy of the area is not very complex, only twenty-one metallic minerals having been definitely identified in the present study. Since about one-third of these minerals are common to all the mines it has been considered advisable to discuss the mineralogy for the area as a

whole, rather than to consider each mine separately. Further, it is convenient to represent in tabular form the reported occurrences of the metallic minerals in the various mines. The table which has been drawn up for this purpose is as follows:

TABLE I

Metallic Minerals in the Ores	Mine						
	Hard Rock	MacLeod- Cockshutt	Little Long Lac	Magnet Consol.	Bankfield Consol.	Tombill	Jellicoe
MAJOR CONSTITUENTS							
Arsenopyrite	146	134	1256	1	12346	1	1
Pyrite	12346	12346	1256	1	12346	1	1
Gold	12346	12346	123456	1	12346	1	1
MINOR SULPHIDES							
Chalcopyrite	16	16	16	1	123	1	1
Cubanite	1						
Galena	16	1	16	1			*
Leucopyrite	1	1	1	1			
Pyrrhotite	16	1	156	1	123		1
Sphalerite	1	16	16		16	1	1
Stibnite			25				1
TELLURIDES							
Coloradoite(?)		1					
Krennerite(?)		1					
SULPHO-SALTS							
Berthierite			6				
Bournonite			125				
Grey Copper	6		16		1		
OTHER METALLICS							
Graphite	1					1	
Hematite	1	1	5				
Ilmenite	1	1	1		123	1	1
Magnetite	1	1	6		6		
Scheelite			1			**	
SUPERGENE MINERALS							
Chalcocite					1		
Limonite			6		16		
Malachite					1		

1—mineral identified in present study.

2—mineral identified by Bruce (1935).

3—mineral identified by Bruce (1936).

4—mineral identified by Bruce (1939).

5—mineral identified by Bruce and Samuel (1937).

6—mineral identified by Thomson (1935).

*—mineral reported by G. C. McCartney (personal communication).

**—mineral reported by P. E. Hopkins (personal communication).

In the following descriptions, arranged in the order in which the minerals occur in the table, the term *bleb* is used in a sense differing from the dictionary definition. The definition implies small drop-like or bubble-shaped masses. The writer uses the term to signify any very small anhedral mass within another, regardless of whether it be angular or rounded. The term, however, does not include minute regular crystal inclusions, such as are found in some sections.

MAJOR CONSTITUENTS

Arsenopyrite (FeAsS). Arsenopyrite has been recognized in polished sections representative of each of the seven mines in the area. In nearly all the sections examined it was the first mineral to crystallize, commonly having assumed lath-, diamond-, or needle-shaped euhedral outlines. In sections from several mines, especially Hard Rock and Bankfield, the grains of arsenopyrite are bounded on two sides by crystal faces, the remaining boundary being more irregular. Such crystals, known as skeleton crystals, characteristically formed where arsenopyrite replaced wall-rock minerals. The crystal faces are an automorphic replacement of the minerals of the wall-rock; the irregular boundary is a contact where replacement is incomplete. Where arsenopyrite is not automorphic it very commonly occurs as granular aggregates, which may be up to 10 mm. in diameter.

The larger crystals and aggregates of grains are commonly broken by fractures; in the aggregates, individuals may be pried away from their neighbors. Lath-shaped crystals are often fractured transversely, the fractures being filled by quartz, carbonate, or metallics. Where fracturing has been complex the arsenopyrite may have a brecciated appearance. Replacement of the walls by the "healing" mineral is common, but in many specimens the opposite walls along fractures match perfectly.

The arsenopyrite crystals average about 0.5 mm. in diameter, but the size varies within wide limits. Tiny euhedra surrounded by pyrite are 0.01 mm. or less in longest dimension; larger lath-shaped crystals are as much as 4 mm. long. The proportion of arsenopyrite in the ores is also variable. Polished sections of some sulphide ores contain very few crystals of arsenopyrite, less than two or three per cent. A specimen of massive arsenopyrite ore from Magnet Consolidated is more than ninety per cent arsenopyrite, the remainder being largely quartz.

The crystallizing power of the arsenopyrite is strong enough to inhibit the growth of contemporaneous inclusions. Later replacements are, however, rather common in some sections. Where arsenopyrite is in great excess over pyrite, pyrrhotite and chalcopyrite may occur as small rounded or irregular blebs in the arsenopyrite. The lack of any regular

arrangement of these inclusions precludes the possibility that they are products of exsolution. In sections where the period of deposition of arsenopyrite is overlapped by that of pyrite, the latter may occur as small euhedral crystals within the arsenopyrite.

Pyrite (FeS_2). Pyrite, like arsenopyrite, was found in specimens from all the mines in the area. Although not constant in its relations to the other minerals, especially quartz and arsenopyrite, it usually exhibits the regular outlines of sectioned cubes or pyritohedra. In vuggy specimens from Hard Rock, MacLeod-Cockshutt, and Little Long Lac mines pyrite encrusts quartz or calcite crystals as clusters of minute euhedra. Although pyrite often shows a strong tendency to assume its crystal outlines, later fracturing or replacement have commonly destroyed what may have been euhedral crystals. As in the occurrences of arsenopyrite, pyrite frequently forms aggregates of anhedral grains, and in some specimens it occurs as narrow veinlets.

Fractures in pyrite are commonly filled with quartz or calcite, sometimes with chalcopyrite. Bruce (1935, p. 39) has figured a specimen from the Little Long Lac mine in which pyrite has been brecciated and cemented with bournonite. The writer had available no specimens showing this condition; the closest similarity was brecciated pyrite cemented with quartz. As in the arsenopyrite, fracture walls may or may not be replaced by the fillings; many examples of both conditions were observed. In general, the pyrite is less fractured than the arsenopyrite, for the most part as a result of its position in the paragenetic sequence. The contrast may be due, in part, to the crystal habit and greater brittleness of the arsenopyrite.

Pyrite crystals are extremely variable in size. The smallest can be seen only with the high powers of the microscope; the largest measured, from the Number 2 vein system at Hard Rock, were just over 30 mm. in diameter. Under such conditions it is difficult to set an average, but for individual crystals, as seen in polished sections, the average diameter approximates 1 mm. The average size of the aggregates of anhedral grains is somewhat in excess of this figure, 2 to 3 mm. being representative. The proportion of pyrite to the other metallics and to the gangue minerals is extremely variable. A specimen from Hard Rock, of iron formation almost completely replaced by sulphides, contains arsenopyrite and two-millimeter diameter pyrite grains in about equal proportions.

Pyrite commonly contains inclusions of other minerals, metallics and quartz. Arsenopyrite occurs as euhedral grains and rarely as rounded blebs. These are a result of the prior crystallization of arsenopyrite; the rounded blebs are probably due to replacement action of the later pyrite. Quartz, where earlier than pyrite, is generally present as euhedral crys-

tals, doubly terminated needles being common. Rounded or irregular inclusions of chalcopyrite and pyrrhotite, usually less than 0.1 mm. in size, are characteristic of much of the pyrite. In many instances they have replaced pyrite along channels of easy access formed by the contact with arsenopyrite or quartz, or by minute cracks in the pyrite. Sphalerite blebs are less common than pyrrhotite and chalcopyrite. In some sections these are associated with the other two, in others the sphalerite forms minute replacement blebs unconnected with either pyrrhotite or chalcopyrite. In none of the sections examined were the inclusions arranged in any regular order; it is unlikely, then, that they have formed as a result of unmixing from solid solution.

Gold (Au). Gold was observed in polished sections from each of the mines. Hand specimens of "high grade" from all but Hard Rock show free gold, sometimes in spectacular amounts. In some, the gold is associated with quartz, generally greyish in color and fairly well fractured. One specimen from Magnet Consolidated shows gold associated with calcite; and in one from Tombill the gold occurs in a blue-black quartz vein near the contact with a black argillite-like greywacke. Gold visible in the hand specimens forms delicate films, leaf-like or dendritic, along fractures in the quartz. In some specimens the gold is more robust, forming aggregates with the characteristic hackly feel.

In the polished sections gold occurs as blebs and veinlets in quartz and in the sulphides. It is associated with galena in sections from MacLeod-Cockshutt, Little Long Lac, and Magnet Consolidated. A section from the latter mine shows a veinlet of galena and gold, in which gold is automorphic against the galena.

In polished sections of average ore the gold occurs as blebs which vary in size from less than 10 to as much as 100, rarely 200 microns, in longest dimension. In some sections only two or three such blebs were observed, in others the number is higher. A specimen of pyritic ore from MacLeod-Cockshutt contains seventeen tiny blebs in an area of about 100 sq.mm. A somewhat larger specimen of similar ore from Hard Rock contains nineteen blebs. In neither of these specimens is gold visible except under high power.

Gold in the finely-divided state occurs as inclusions, but in sections of high grade ore it is itself seen to contain inclusions, galena and chalcopyrite being most common. Very minute specks of other minerals, too small for optical or etch tests, were observed in some sections. These may be of telluride nature, as in sections from the 210 Quartz Vein at MacLeod-Cockshutt. Inclusions of galena are rounded and are probably contemporaneous with the gold. Chalcopyrite inclusions are generally automorphic, thus indicating their position in the paragenetic sequence.

The very minute blebs of gold present in the sulphides and gangue of average ore were distinguished from chalcopyrite by careful observations of color, surface texture, and behavior under crossed nicols. Even the smallest grains are bright yellowish-orange against chalcopyrite, and the surface of such grains has a rather granular or roughened appearance, probably a result of the softness of the gold. The gold of these inclusions does not seem to show any preference for pyrite over arsenopyrite; where more gold is associated with pyrite, it is very largely due to the fact that there is more pyrite than arsenopyrite in the section. The same holds true for arsenopyrite. M. H. Haycock, reporting the results of grain analyses of a number of polished sections of MacLeod-Cockshutt ore, in a personal communication to H. F. Morrow (1940, p. 26) stated that 67 per cent of the gold was in pyrite, the remainder in the gangue. The present study indicates that the proportion is about even, gold generally being found wherever the solutions have had easiest access. The presence of tiny gold inclusions in pyrite or arsenopyrite unconnected with the gangue by cracks or other visible channels, suggests the possibility that the gold may be contemporaneous with the sulphides. In such cases great care must be taken to determine whether or not most of the gold in that particular section occurs in the gangue, that is, is late gold. Consideration must also be taken of the third dimension; many supposedly unconnected blebs were seen to conform to one or more crystal outlines on the mineral in which they occur. This gold, then, may well have come in along a channel normal to the plane of the section. Some of the gold merely fills open spaces; in other specimens, or even in parts of the same specimen, the gold may be a replacement of sulphides or gangue minerals.

MINOR SULPHIDES

Chalcopyrite (CuFeS_2). In most of the specimens available, chalcopyrite occurs in minor amounts as anhedral blebs in sulphides or gangue. In five of the sections examined, of which two were from MacLeod-Cockshutt, two from Bankfield, and one from Tombill, chalcopyrite is the important sulphide.

Few examples of chalcopyrite with crystal outlines were observed. The most common occurrence of the minerals is as blebs in pyrite and arsenopyrite, as described above under those minerals. In several sections, however, chalcopyrite occurs as a fracture filling in pyrite and arsenopyrite. Several places were found where it is automorphic against the calcite of the gangue, and it has been mentioned above that it occasionally presents crystal faces against gold. In the sections where sphalerite occurs in fairly large masses, chalcopyrite is found as blebs in the sphalerite. These are further discussed under that mineral.

The blebs of chalcopyrite in pyrite and arsenopyrite are small, usually less than 100 microns in diameter. Irregular areas of chalcopyrite in quartz or carbonate gangue are larger and measure as much as 1000 microns. In the specimens containing an average amount of chalcopyrite there is less than one per cent of the mineral. In the five sections mentioned above, chalcopyrite forms more than 90 per cent of the surface area.

The age relations between pyrite, quartz, and chalcopyrite are well illustrated by the Tombill specimen in which chalcopyrite conforms to crystal outlines of quartz, pyrite, and arsenopyrite. Except for one occurrence of cubanite, and those cases in which chalcopyrite is so abundant that it has surrounded earlier crystals, the mineral contains no inclusions.

Cubanite ($\text{Cu}_2\text{S} \cdot \text{Fe}_4\text{S}_5$). In one section from Hard Rock a pinkish-cream mineral occurs as a slender lath in a chalcopyrite bleb in pyrite. The strong anisotropism, color, and association with chalcopyrite and pyrrhotite established its identity. It was much too small to identify positively by microchemical or etch methods.

Galena (PbS). Galena was identified in polished sections from Hard Rock, MacLeod-Cockshutt, Little Long Lac, and Magnet Consolidated. From each of the latter two mines it is represented in only one section; it was identified in six from the 210 Quartz Vein at MacLeod-Cockshutt. The mineralogy of the Magnet Consolidated specimen, from the drag-fold on the 1080-foot level, except for the presence of arsenopyrite, closely resembles that of the MacLeod-Cockshutt specimens which contain no arsenopyrite. It is possible that the ore bodies are similar in nature and origin.

In the Little Long Lac specimen galena is associated with calcite and chalcopyrite. It is automorphic against the calcite, but conforms to the chalcopyrite. In the other specimens galena is associated with gold, both occurring as blebs and veinlets in fractures in the quartz. The relations between galena and gold indicate that the two minerals are contemporaneous; segmented veinlets are common in which the contacts between gold and galena are quite smooth. There is nothing to suggest replacement of the one mineral by the other.

An euhedral lath-shaped telluride occurs as an inclusion in one of the sections from MacLeod-Cockshutt. This is the only mineral inclusion other than gold, except for places where galena has grown around quartz or pyrite crystals, that has been observed.

Leucopyrite (Fe_3As_4). In sections from the four easternmost mines of the area leucopyrite has been identified, associated closely with arsenopyrite, pyrrhotite and pyrite. It occurs as dendritic rods in a manner

almost identical with that illustrated by G. C. Ridland (1941, fig. 13) and also as small prisms, similar to those mentioned in his descriptions of the mineral. The best examples of the present occurrence were seen in one section from Magnet Consolidated, in which the leucopyrite is intergrown with pyrrhotite as dendrites. In the same section it occurs with pyrite as short curved prisms, and with arsenopyrite in dendritic form; it is later than both arsenopyrite and pyrite. In sections from the other three mines the proportion of short prisms to dendrites is about one to one.

The dendrites average 200 to 300 microns in length; the shorter prisms are much less, about one-tenth the length of the dendrites. The amount of leucopyrite in any section is considerably less than one per cent.

The identification of the mineral was based upon its optical properties combined with the peculiar manner of growth. Etch tests were run on some of the specimens, the results agreeing closely with those given by Short (1940, p. 161).

Pyrrhotite (FeS_{1+}). With the exception of Tombill, pyrrhotite was found in polished sections from all the mines in the area. It is probable that more sections of the Tombill ore would have revealed its presence there also. In only one specimen, from a diamond-drill intersection of the West ore zone at MacLeod-Cockshutt, was pyrrhotite present in more than minor amounts.

Pyrrhotite commonly occurs as blebs and veinlets in pyrite, arsenopyrite, and the gangue minerals. The blebs are rounded or irregular in outline, in some places conforming to the crystal outlines of the mineral in which they occur. A few specimens were noted in which pyrrhotite is automorphic against chalcopyrite or carbonate, but no single crystals of pyrrhotite were observed. In some specimens pyrrhotite occurs as fairly large grains in the quartz or other gangue minerals. Such large pyrrhotite masses may contain small replacement blebs of chalcopyrite. The mutual age relationships of chalcopyrite and pyrrhotite are uncertain, but it is probable that the latter is the older. This is suggested by the fact that, where pyrrhotite occurs as blebs in pyrite, chalcopyrite commonly occupies a peripheral position in the inclusion, apparently having replaced the pyrrhotite along its contact with pyrite. These facts are in accord with Schwartz's (1937) observations that the two minerals are in part contemporaneous, but with most of the chalcopyrite somewhat later than the pyrrhotite. An interesting occurrence is as minute ovoid blebs in the magnetite of the iron formation ore from the Hard Rock mine.

Sphalerite (ZnS). Sphalerite was identified in specimens from all but the Magnet Consolidated mine. It is possible that additional sections from that mine would indicate its presence in those ores also.

The mineral occurs in pyrite and arsenopyrite as minute blebs similar to those of pyrrhotite and chalcopyrite. It also occurs as larger masses in the gangue. Wherever it occurs in the larger masses it characteristically contains rounded or ovoid, sometimes angular, minute inclusions of chalcopyrite arranged in a regular manner, possibly along certain crystallographic directions in the sphalerite. These blebs are believed to be ex-solution blebs—a view to which support is lent by their regular arrangement. Even the largest sphalerite areas measure only slightly more than 1 mm. across, so that the amount in a section, as of the other minor sulphides, is generally less than one per cent.

The smaller blebs of sphalerite in pyrite and arsenopyrite are difficult to identify positively. The optical properties have been used to a great extent. It was found that, using the highest power dry objective and ocular combination, with a high intensity lamp and nicols completely crossed, the yellowish brown internal reflection which characterizes the mineral was well brought out.

Stibnite (Sb_2S_3). This mineral was identified in only one section, one which came from the Jellicoe mine. It was recorded by Bruce (1935, p. 40) from the Little Long Lac mine, but none was found in the present material.

In the single occurrence stibnite is associated with chalcopyrite and arsenopyrite; it is later than both those minerals. The mottled appearance, as suggested by Short (1940, p. 114), is probably a result of the radiating, prismatic structure. It may, however, be due to polysynthetic twinning which, under certain conditions, gives an appearance of undulatory extinction as noted by Schneiderhöhn and Ramdohr (1931, p. 79).

The mineral forms a small area 0.2 mm. wide, and 0.9 mm. long. The action of the etch reagents so damaged the specimen as to make it useless for photographic purposes. The identification of the mineral is based on its optical character and its reactions with the standard etch reagents.

TELLURIDES

In his investigation of the mineralogy of the 210 Quartz Vein at MacLeod-Cockshutt, Morrow (p. 39) obtained a positive test for tellurium. The satisfactory identification of tellurides has not been possible in the present study, although especial care was taken with all suspected minerals. Only in the polished sections from the MacLeod-Cockshutt 210 Quartz Vein were there observed any possible tellurides. In these sections however, occur three minerals which may be tellurides.

A lath-shaped, creamy-white mineral associated with galena may be *Krennerite* ($\text{Au,Ag}\text{Te}_2$). This mineral is anisotropic, but the high reflectivity of the surrounding galena prevented identification of the colors.

Continuous scratches of about equal depth cross both minerals, indicating the hardness of the lath-shaped mineral to be somewhat less than the value C assigned to krennerite by Short. Etch tests would have destroyed the section; as a result, the identification as krennerite is not to be regarded as definite.

A pinkish-gray, isotropic mineral associated with, and of approximately the same hardness as galena, is tentatively identified as *Coloradoite* (HgTe). The grains are too small to afford an accurate basis for etch reaction.

The third mineral could not be even tentatively identified, and is referred to as *Mineral X*. The color is somewhat greenish-yellow; under crossed nicols this varies through shades of blue as the stage is rotated. The hardness is about the same as that of galena, B. As with the other two minerals, etch tests could not be made without loss of the sections.

SULPHO-SALTS

Bournonite ($\text{Cu}_2\text{S} \cdot 2\text{PbS} \cdot \text{Sb}_2\text{S}_3$). This mineral was identified in several hand specimens and in one polished section from the Little Long Lac mine. In the former it occurs as irregular veinlets and blebs associated with chalcopyrite in quartz. In the polished section it occurs as irregular blebs in pyrite; at one place the bournonite appears to be automorphic against chalcopyrite, but the relation is uncertain. In general the mineral is not automorphic, but conforms to the surrounding minerals, or to the walls of the fractures in which it may occur.

The identification of bournonite in the polished section was based on its optical character and reaction to the standard etch reagents. In the hand specimens the somewhat conchoidal fracture, brittleness, low hardness, metallic luster, and steel-grey color and streak served to identify the mineral.

Grey Copper ($5\text{Cu}_2\text{S} \cdot 2(\text{Cu}, \text{Fe})\text{S} \cdot 2\text{As}_2\text{S}_3$). This mineral was identified in polished sections from Little Long Lac and Bankfield. The circumstances of its occurrence suggest that it may also be present in most of the other mines. It occurs as very small rounded and irregular blebs in pyrite and arsenopyrite.

The close similarity in color between grey copper and sphalerite may have resulted in some misidentification. Grey copper is somewhat lighter in color, and does not have the yellowish-brown internal reflection noted for sphalerite. Etch reactions were inconclusive because of the minuteness of the inclusions. It is possible that, when dealing with such small grains, electrolytic action, inhibiting the normal reactions, may be set up within the drop of reagent.

OTHER METALLICS

Graphite (C). Flakes of graphite were identified in polished sections from Hard Rock and Tombill. The Tombill graphite is visible along seams in a hand specimen containing a high proportion of chalcopyrite. The association of graphite seams with chalcopyrite is not uncommon in some of the mines of the Canadian Shield. A polished section containing graphite shows short flakes of a brownish-grey mineral, soft, and negative to all reagents. Careful observation was made to ascertain whether there were four or only two extinctions per revolution. The mineral extinguished only twice in 360 degrees, so is graphite rather than molybdenite. The graphite in the Hard Rock sections occurs as very small brownish flakes, distinctly anisotropic. They are regularly arranged with longest dimensions parallel in a sheared dark greywacke. Their similarity to the mineral called graphite in the Tombill section indicates their identity.

The origin of the graphitic carbon is an interesting, but conjectural matter. The associated rocks are sediments, and it is possible that the graphite is of organic origin, derived from primitive organisms.

Hematite (Fe_2O_3). Hematite was positively identified in polished sections of ore from MacLeod-Cochshutt. In the best specimen, magnetite-bearing iron formation has been folded and has fractured parallel to the bedding. In this fracture two-millimeter euhedra of pyrite have crystallized, preserving their outlines against quartz. The quartz-pyrite contact has served as an effective channel for the ingress of solutions which deposited hematite. In some places, separating the hematite from pyrite, is a thin band of a transparent mineral exactly like quartz, but having a reddish color in obliquely reflected light. It is probably jasper.

The hematite forms narrow bands 0.1 mm. in width, having minutely irregular contacts with quartz or jasper and pyrite. In other specimens, in which the hematite was identified by similarity with that already described, it occurs as rounded inclusions, or as arborescent and irregular replacements of pyrite. The hematite in the quartz-pyrite veinlet in folded iron formation carries some inclusions of pyrite and magnetite. The magnetite was probably caught up from the wall rock; the pyrite is euhedral and represents material around which the hematite has grown.

Hematite was identified by its optical and chemical properties. It is negative to all the standard etch reagents; and in vertically reflected light is distinctly bluish against pyrite. It is not strongly anisotropic under crossed nicols, but with a high intensity lamp shows bright red internal reflection.

Ilmenite (FeTiO_3). A mineral, the description of which answers most

closely to that of ilmenite, occurs in polished sections from all the mines but Magnet Consolidated. It occurs as irregular grains in the gangue, and as veinlets cutting pyrite or arsenopyrite. In some specimens it may form as much as one per cent of the section, but in general is considerably less. Larger masses measure up to 0.5 mm. in diameter; smaller grains are less than 0.1 mm.

The identification of the mineral was based on the following criteria: Color—Grey, lighter than sphalerite, sometimes having a brownish tinge. Hardness—Very hard, cannot be scratched by a sharp needle with pressure. Optically—Distinctly anisotropic through shades of grey and brownish-grey, two extinctions per revolution. Under only one nicol the mineral shows a strong reflection pleochroism through light gray and brownish-grey. Internal reflection varies from slight to distinct, with colors of yellow-brown to red-brown. The characteristic twinning lamellae are irregularly spaced. These lamellae show up well under polarized light, or better under crossed nicols. Chemically—Negative to all standard etch reagents.

Magnetite (Fe_3O_4). Magnetite occurs in conspicuous amounts in specimens and polished sections of ore from the Hard Rock No. 2 and No. 30 vein systems, and from the MacLeod-Cockshutt North and South ore zones. Small grains of an isotropic grey mineral in sections of ore from most of the other mines are possibly magnetite, but their identity is uncertain. Euhedral crystals of magnetite are not uncommon, but in general the mineral forms irregular grains. In one of the Hard Rock specimens the magnetite grains almost everywhere conform to quartz outlines.

The grains are small, usually less than 0.05 mm. in diameter. Larger areas of magnetite are composed of aggregates of individual grains, some of which are euhedral, others irregular. Where magnetite forms a conspicuous part of a section it may be 25 per cent, or in some specimens more than 60 per cent, of the polished area. Where it occurs in only minor amounts it is less than one per cent.

The magnetite in the specimens from Hard Rock and MacLeod-Cockshutt is part of the original iron formation which has not been replaced by the later sulphides. It is probable that any magnetite in other sections is also earlier than the ore minerals, being either detrital or formed in the unaltered rock prior to the sulphide mineralization.

Scheelite (CaWO_4). Although it has not been possible for the writer to study the relationships of this mineral, it is included herein for the sake of completeness. Available information indicates the occurrence of scheelite at Little Long Lac and, in minor amount, at Tombill. In one specimen, from the former mine, scheelite occurs as small bunches and segments in

quartz veinlets. It was not observed in any of the polished sections studied.

MAJOR NON-METALLICS

Quartz (SiO_2). Quartz occurs as euhedral crystals, veinlets, and irregular masses in specimens from all the mines in the area. It is the most abundant gangue mineral; in nearly all the specimens occupying a considerable proportion of the area of the section. It was one of the earliest minerals to crystallize, the period of its deposition sometimes being long continued so that it forms small euhedral crystals in vuggy quartz veins. Later ages of quartz were seen where the narrow quartz veinlets have cut through existing minerals. In general, the quartz is similar to that of other areas, showing considerable variation in color from white "bull" quartz, through shades of grey, to the blue-black quartz of the Tombill specimen noted in the discussion of gold. The degree of fracturing sustained by quartz is also variable; some, which is badly shattered, contains considerable free gold. Some quartz is rather sugary, in other specimens it is almost chalcedonic. Jasper, a variety of quartz, was observed in sections from MacLeod-Cockshutt where it is associated with hematite in quartz-pyrite veinlets.

Calcite (CaCO_3). Calcite is second only to quartz in quantity as a gangue mineral. It was observed in sections from all the mines reported upon. Generally one of the last minerals to crystallize, it conforms to the crystal outlines of all but gold, against which it is occasionally automorphic. It is a common constituent of the wall rock, but occurs also in the quartz veins. In some specimens calcite crystallized prior to quartz; it occurs at the contact of the quartz veins with the wall rock, and is automorphic against quartz except where it has been replaced. Calcite was found in some vuggy quartz veins where it was deposited upon euhedral quartz crystals. In one specimen from Little Long Lac calcite forms rhombohedral crystals deposited directly upon light grey arkose, clusters of minute pyrite crystals were in turn deposited on the calcite. In many specimens late fractures are filled with narrow quartz-calcite veinlets, or with veinlets of calcite alone. Some specimens show calcite which is of possible secondary (supergene) origin.

SUPERGENE MINERALS

Minerals of supergene origin are neither common nor important in the Little Long Lac area. A single polished section from Bankfield kindly loaned the writer by Ellis Thomson, contains chalcocite, limonite, and malachite. Bruce (1935, p. 49) noted an oxidized zone at this mine ex-

tending to depths varying from two and one-half to ten feet. It is probable that the polished section examined came from this zone. Economically the occurrence is unimportant, but from the scientific point of view it is interesting as representing one of the few oxidation zones recorded in the Canadian Shield.

Chalcocite (Cu_2S). Replacement veinlets in chalcopyrite and pyrite are composed of limonite and a soft, blue-grey mineral identified as chalcocite. Limonite forms the medial portion of the veinlets, chalcocite being found on either side. The replacement origin of the chalcocite is indicated by its very irregular contact with the primary minerals. Its supergene character is suggested by the numerous transverse cracks which may represent shrinkage due to drying from a colloidal state.

Limonite (hydrated iron oxides). Limonite occurs in replacement veinlets cutting chalcopyrite and pyrite, and as clusters of radiating needles (goethite?) associated with the same minerals. Thomson (p. 40) recorded it as occurring fairly commonly as tiny veinlets or small inclusions in the gangue or other iron minerals. In addition to the section from Bankfield, a mineral identified as limonite was observed in several sections where it is the latest mineral present. It occurs as a hard grey mineral appearing grey by vertically reflected light.

Malachite ($\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$). A mineral occurring as clusters of radiating needles, grey by vertically reflected light, but brilliant green under crossed nicols or obliquely reflected light, was identified as malachite. It is later than limonite and chalcocite, which form a rim separating it from the unaltered chalcopyrite from which it was derived. Malachite is present in only minor amount, less than five per cent, in the one section in which it was observed.

CONCLUSION

The above extended descriptions of the metallic and major non-metallic minerals of the Little Long Lac area supplement the writer's earlier paper which is concerned, for the most part, with their age relationships. As a result of the study of the major sulphides the writer allocates the deposits to Lindgren's upper hypothermal, or lower mesothermal, zone. Instrumental observations made by F. Gordon Smith, at the University of Toronto, on pyrite from the Hard Rock mine indicate that it crystallized at temperatures lying within the range suggested for those zones.

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NOTES AND NEWS

OCCURRENCE OF CHRYSOBERYL AT WAKEFIELD, CARROLL COUNTY, NEW HAMPSHIRE*

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A pegmatite exposed on the R. B. Weeks property, Wakefield, N. H., is one of several recently investigated by the Bureau of Mines, United States Department of the Interior, in connection with studies on the development and beneficiation of New England beryl ores. The pegmatite is situated in the northern part of Wakefield, about 1 mile west of Province Lake and 5 miles east of Ossipee, and has been worked for feldspar. It is circular or oval in shape and apparently nearly vertical in dip. Most of the beryl formerly visible in the quarry has been removed in the course of sampling.**

Mineralogically, the sample submitted to the Eastern Experiment Station is that of a simple pegmatite. It consists chiefly of coarse alkali-feldspar, is rather poor in quartz, and carries only minor amounts of muscovite. Beryl is the principal accessory mineral, constituting several per cent of the sample submitted and certainly far less of the total pegmatite. A little of the blue tourmaline and red garnet so common in New England pegmatites, and the chrysoberyl described below complete the roster of minerals identified in the ore.

A curious yellow to apple-green mineral, coating or cutting beryl or lying in feldspar immediately adjacent to beryl crystals, was first noticed by Frederick W. Horton, who brought it to the writer's attention. This mineral has the usual optical and physical properties of chrysoberyl, and the identification was confirmed by powder diffraction patterns obtained by H. F. Carl from a few grains isolated from the surrounding rock with considerable difficulty.

The mineral is everywhere closely intergrown with muscovite, and the intergrowth is frequently accompanied by quartz. In favorable specimens it can be seen that this associated quartz is concentrated along cracks in feldspar or along crystal boundaries. It must be of very late crystallization. This is true also of the muscovite-chrysoberyl intergrowth, for its distribution seems to require the previous presence of beryl crystals, feldspar crystals, or preferably beryl-feldspar boundary surfaces. It is not clear from the sample material whether this late generation of quartz,

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** Field information from unpublished Bureau of Mines and Federal Geological Survey Reports.

muscovite, and chrysoberyl is merely a vein and fracture filling or has been introduced by replacement, but the close association of beryl and chrysoberyl certainly suggests the latter.

The writer has had no opportunity to study the occurrence in the field and cannot say whether the chrysoberyl is disseminated throughout the deposit or is confined to the outcrops from which the bulk sample was taken. In this sample, however, it is not at all uncommon. Streaks of the chrysoberyl-muscovite intergrowth lying along beryl-feldspar boundary surfaces are generally attached more strongly to beryl than to feldspar and, when the beryl is broken out of the matrix, usually come along with it as a coating, leaving the feldspar nearly or quite barren. It is impossible to estimate accurately the percentage of chrysoberyl present in our sample; it is certainly less than a hundredth and probably less than a thousandth of the beryl.

Although there are 14 previously recorded occurrences of chrysoberyl in New York and New England, the writer has been unable to find any reference to the Wakefield locality. Of the known occurrences, 12 are in Maine (1), 2 in New York (2), 1 is in Connecticut (3), and 1 in New Hampshire (4). The new locality, near the Maine border, is about 50 miles due east of the only other New Hampshire occurrence (Orange Summit) and lies about 50 miles south-southwest of the general area in which most of the Maine finds have been made.

The occurrence of chrysoberyl in New England has been known since early in the nineteenth century, and all save one of the previously recorded occurrences, that at Hartford, Maine, were already on record by 1885. Of the 12 Maine localities in which chrysoberyl is said to have been found, one (Buckfield) is questioned by Palache (1*e*), the evidence for three (Stowe, Peru, and Canton) seems to consist solely of a paraphrase of a letter from N. H. Perry (1*c*) with no details concerning either locality or occurrence, and three (Auburn, Greenwood, and Topsham) are represented only by specimens in the National Museum. Perry's notice mentions "small dark-colored crystals in the fibrolite at Stoneham," and the National Museum study collection contains a specimen said to have come from Stoneham. Notice of the specific locality either has been lost or was never properly recorded. In a letter to the writer, Dr. Palache states that the Harvard-collection chrysoberyl specimens "labeled from Buckfield, from Greenwood, and from Sumner . . . were undoubtedly from the Hartford locality." He also mentions a Harvard specimen from Minot Township and suggests that the National Museum specimen labeled "Auburn" might be from that locality. Thus, the imposing total of 12 Maine occurrences is reduced to 2, Hartford and Norway, which have been studied adequately. If successful collections have been made from

Haddam, Connecticut, or Orange Summit, New Hampshire, in recent years, nothing has been published concerning them.

All this makes it clear that chrysoberyl is an exceptionally rare mineral, so rare that generalizations concerning its occurrence are of dubious value. In New England it seems to be associated invariably with dark tourmaline and red garnet, but this association can be claimed for almost any pegmatite mineral in New England. At Hartford, chrysoberyl occurs in a highly siliceous pegmatite, but at Wakefield the part of the pegmatite in which it has been found is singularly poor in quartz. It may occur with or in the absence of beryl, as at Wakefield and Hartford, respectively. No beryl was noted by Hubbard in the original notice of the Orange Summit occurrence (4), and although beryl was subsequently collected from Haddam, Conn. (5), nothing was said of its relation to the site of the original chrysoberyl find.

To date, no specimens of chrysoberyl have been described as occurring in the phosphate-rich pegmatites characterized by the presence of rare manganese-iron-lithium phosphates or by large amounts of apatite, and it may be suspected that the relative concentration of phosphate ion determines whether a given pegmatite carries chrysoberyl or herderite. Unfortunately, herderite has been reported from three of the questionable chrysoberyl localities cited above (Stoneham, Greenwood, Auburn), and from Stoneham beryllonite has also been described. In each instance, however, the chrysoberyl "locality" consists of no more than a town name, and it is possible that chrysoberyl and herderite (or beryllonite) might have come from the same town but from very different pegmatites.

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- b. Buckfield—Bastin, E. S., *U.S.G.S. Bull.*, **445**, 71 (1911).
- c. Canton—Perry, N. H., *Am. Jour. Sci.*, 3d Ser., **29**, 263 (1885); specimen in Columbia University Museum.
- d. Greenwood—specimen in United States National Museum; specimen in Harvard University Museum, probably from Hartford.
- e. Hartford—Palache, C., *Am. Mineral.* **9**, 217 (1924); specimen in United States National Museum.
- f. Minot—specimen in Harvard University Museum, possibly from Auburn.
- g. Norway—Verrill, A. E., *Proc. Bost. Soc. Nat. Hist.*, **7**, 423 (1860); Perry, N. H., *op. cit.*; Bastin, E. S., *op. cit.*, 78.
- h. Peru—Perry, N. H., *op. cit.*
- i. Stoneham—Perry, N. H., *op. cit.*; specimen in United States National Museum.
- j. Stowe—Perry, N. H., *op. cit.*
- k. Sumner—specimen in Harvard University Museum, probably from Hartford.
- l. Topsham—specimen in United States National Museum.

2. *New York:*

- a. Saratoga Springs—Steele, J. H., *Am. Jour. Sci.*, 1st Ser., **4**, 37 (1821).
- b. New York City—Moses, A. J., *Am. Jour. Sci.*, 4th Ser., **12**, 104 (1901).

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Haddam—Haüy, R. J., *Journal des Mines*, **30**, 179 (1811).

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Orange Summit—Hubbard, E. O., *Am. Jour. Sci.*, 2d Ser., **11**, 424 (1851).

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A METHOD FOR ISOLATING GRAINS MOUNTED IN INDEX OILS*

MARIE L. LINDBERG

In investigating an assemblage of minerals, as in the study of detrital heavy minerals for correlation purposes, an estimation of the relative abundance of each mineral is made by counting the component mineral grains in an oil mount. The minerals are then identified by their crystal form and grain shape, and by their optical properties. The mineral grains are placed on a slide, and an index oil is spread thinly over them, forming a flat surface, above which the grains should not project. A cover glass need not be used when counting grains. If an unknown mineral is present, it may be isolated for further study in the manner outlined in this paper.

In the method described by Reed¹ and that by Calkins² the grain is removed from the oil by means of a wire that has been dipped into an adhesive substance (Canada balsam, vaseline, etc.). In the procedure here described the grain is removed by means of a glass dropper which offers the advantage of transferring the unknown mineral without the use of Canada balsam or vaseline, which are slowly soluble in index oils.

A low-power objective is used to give the maximum amount of working room between the slide and the objective. The dropper is made by heating and pulling out a glass tube having an inside diameter of 4 mm., so that the capillary has a diameter slightly larger than the grains on the mount. A bulb made from a section of rubber tubing about 5 cm. long, closed at one end, is fitted to the dropper. The completed dropper is 12–15 cm. long. This glass dropper is held nearly vertical over the unknown mineral, and then lowered into the oil. The mineral with some immersion oil is sucked into the dropper and transferred to a clean slide without release of pressure on the bulb of the dropper. If the first slide is thick with

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¹ Reed, R. D., Some methods for heavy mineral investigations: *Ec. Geology*, **19**, 332 (1924).

² Calkins, F. C., Transfer of grains from one liquid to another: *Am. Mineral.*, **19**, 143–149 (1934).

grains, it may be desirable first to isolate the mineral from the others with a steel needle.

On the new slide the excess liquid is absorbed on lens paper wrapped around a pointed match stick. Care should be taken not to touch the mineral grain with the lens paper as the grain may adhere to the paper. Two procedures may be used in removing the remaining index oil: (1) The new index oil may be added to the slide to dilute the first oil. The excess liquid is taken up with a fresh piece of lens paper. Application and removal of the oil is repeated several times until there is no effect from the old oil. More applications are needed in the case of widely separated index oils than in oils with indices in the same range. This method for removing index oils is that which has been used in the Geological Survey for changing index oils in glass prisms. (2) A few drops of acetone may be placed on the slide. The acetone is immiscible with the index liquid and pushes the oil away from the mineral grain, where it is removed with a fresh piece of lens paper. Washing with acetone is repeated until the mineral grains are perfectly dry and clean. Three to five treatments are necessary. If difficulty is experienced in removing the index oil, a treatment with xylene, which is miscible with both the index oils and with acetone, may be substituted for one of the acetone washings. The last washing should be with acetone as the xylene does not evaporate quickly.

Any desired index oil may be placed on the mineral after removing the first oil. If more than one oil is necessary, the preceding oil may be removed by repetition of either procedure. A cover glass should be used when determining the index of refraction of the mineral. Tweezers are helpful in removing the glass for further study with index oils.

If it desired to preserve the minerals in the original mount, they can be washed from the slide into a 5 or 10 cc. beaker with a little acetone from the dropper. The excess liquid is decanted. The minerals may be washed in xylene, in which the index liquids are miscible, and dried in acetone. They may then be mounted in Canada balsam.

PROCEEDINGS OF SOCIETIES

THE PHILADELPHIA MINERALOGICAL SOCIETY

The Academy of Natural Sciences of Philadelphia, March 2, 1944

A meeting was held on the above date with Dr. W. Hersey Thomas presiding. Sixty-five members and visitors were present.

Dr. S. J. Shand, Professor of Geology at Columbia University addressed the Society on "Meteorites and the Interior of the Earth." Several lines of evidence indicate that the thickness of the earth's crust is somewhere in the vicinity of twenty miles. A number of slides were shown illustrating several well known meteorite falls and also charts illustrating seismic vibrations through the different layers of the earth.

Meeting of April 6, 1944.

Dr. W. Hersey Thomas presided with sixty-six members and visitors present. Harold Arndt announced the death of Dr. Benjamin L. Miller of Lehigh University and Harry Trudell read a memorial: "With the passing of Dr. Benjamin L. Miller the Philadelphia Mineralogical Society has lost a very warm friend. He could always be depended upon to give a good word and generous boost for our group which dates from 1913 when he was a Professor of Geology at the Wagner Free Institute of Science and since that time has given talks to our meetings on various occasions. We have ever found in him a fund of charming good fellowship; he seemed to radiate kindness and inspiration wherever he went.

"His knowledge and interpretation of the Geology and Mineralogy of Pennsylvania has been very thorough and outstanding, and the loss to our State is most lamentable. His admirers are certainly legion, and the pleasantest memories will long survive in the hearts of those who knew Dr. Miller."

John Cochrane gave a talk on "Industrial Applications of the Lesser Known Elements." Nine of the rarer elements were dealt with, namely beryllium, titanium, zirconium, hafnium, columbium, tantalum, molybdenum, tungsten and rhenium. Most of these metals were exhibited in their pure state.

Louis Moyd who returned from Canada related some of his mining experiences in the Bancroft, Ontario, region and the Great Slave Lake district.

Meeting of May 4, 1944

Dr. W. Hersey Thomas presided, with 61 persons present.

Mr. Samuel G. Gordon addressed the society on "The Mineralogy of the Tin Mines of the Cerro de Llallagua, Bolivia." A monograph describing this unique deposit is now in preparation. In less than forty years, these mines have yielded about a seventh as much tin as was produced in thirty centuries of mining in the whole of Cornwall. The tin veins occur principally in a quartz porphyry, which is a striking example of metasomatism on a large scale. The feldspars and biotite were successively altered to muscovite, and then to tourmaline and quartz, *prior* to the formation of the mineral veins. The larger veins were composite in character with an earlier generation of quartz, bismuthinite, cassiterite, wolframite, and apatite, followed by a central filling of pyrrhotite—the second stage of the mineralization. A third stage occurred in which the pyrrhotite was replaced along parting planes, by marcasite and pyrite, accompanied by deposition of franckeite, wurtzite, galena, siderite, sphalerite, and stannite. The sulfide deposition (II and III Stages) not only filled the central spaces of the larger veins and isolated pockets in the smaller veins, but extended to the margins of the fractures (beyond the tin mineralization) in all directions, and finally closed the channels below. Most of the minerals which replaced the pyrrhotite inherited a definite

crystallographic orientation from the latter, which remained after most of the pyrrhotite had been removed by supergene solutions. The removal of the pyrrhotite resulted in honeycomb (boxwork) residual masses of marcasite and pyrite with their inherited orientations. Goethite, variscite, wavellite, vivianite, paravauxite, childrenite, and greenockite were deposited on a large scale by supergene solutions. These abundant phosphates were derived from apatite, a common gangue mineral in the richer veins. Mineralogically the deposit is of interest because of the exceptionally large and perfectly developed crystals of bismuthinite, stannite, wurtzite, wavellite, and vivianite, as well as for the several minerals belonging to the vauxite group. Few of these extraordinary specimens were preserved. Thorium-free monazite was abundant, as was greenockite in minute cyclic-twinning crystals. The sixty minerals were illustrated by 80 crystal drawings, 30 photographs and a number of maps. The composition of the minerals described was expressed by a combination of chemical and structural formula, for example: greenockite, $\alpha[\text{CdS}]_2[\text{C6mc}]$.

JOHN FRANKENFIELD, *Secretary*

DISCREDITED SPECIES

Collophane, Nauruite, Monite, Ornithite, Pyroclasilite (= Francolite or Dahllite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 215–232 (1943).

Metabrushshite, Stoffertite (= Brushite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 215–232 (1943).

Bismutosphaerite, Hydrobismutite, Basobismutite, Normannite (= Bismutite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 521–535 (1943).

Agricolite (= Eulytite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 536–540 (1943).

Rhagite (= Atelestite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 536–540 (1943).

Zeugite (= Martinite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 215–232 (1943).

Pyrophosphorite (= Whitlockite)

CLIFFORD FRONDEL. *Am. Mineral.*, **28**, 215–232 (1943).

DISCUSSION: Frondel shows that martinite and whitlockite give identical x-ray powder patterns and differ only in that martinite contains CO_2 and H_2O . He suggests that the name martinite be dropped. However, martinite (Kloos, 1888) not only has priority over whitlockite (1941), but the original description and the later observations of Larsen (1921) and of Hendricks, Hill, Jacob and Jefferson (1931) characterized the mineral well enough to justify the retention of the name martinite, even if a single name is to be used.

It is suggested that both names be retained; whitlockite to be restricted to $\beta\text{-Ca}_3\text{P}_2\text{O}_8$, martinite to be used for the corresponding mineral containing CO_2 and H_2O . Martinite would then bear the same relation to whitlockite as francolite does to fluorapatite.

MICHAEL FLEISCHER